Matter-Antimatter Oscillations at 2.8 Trillion Hertz

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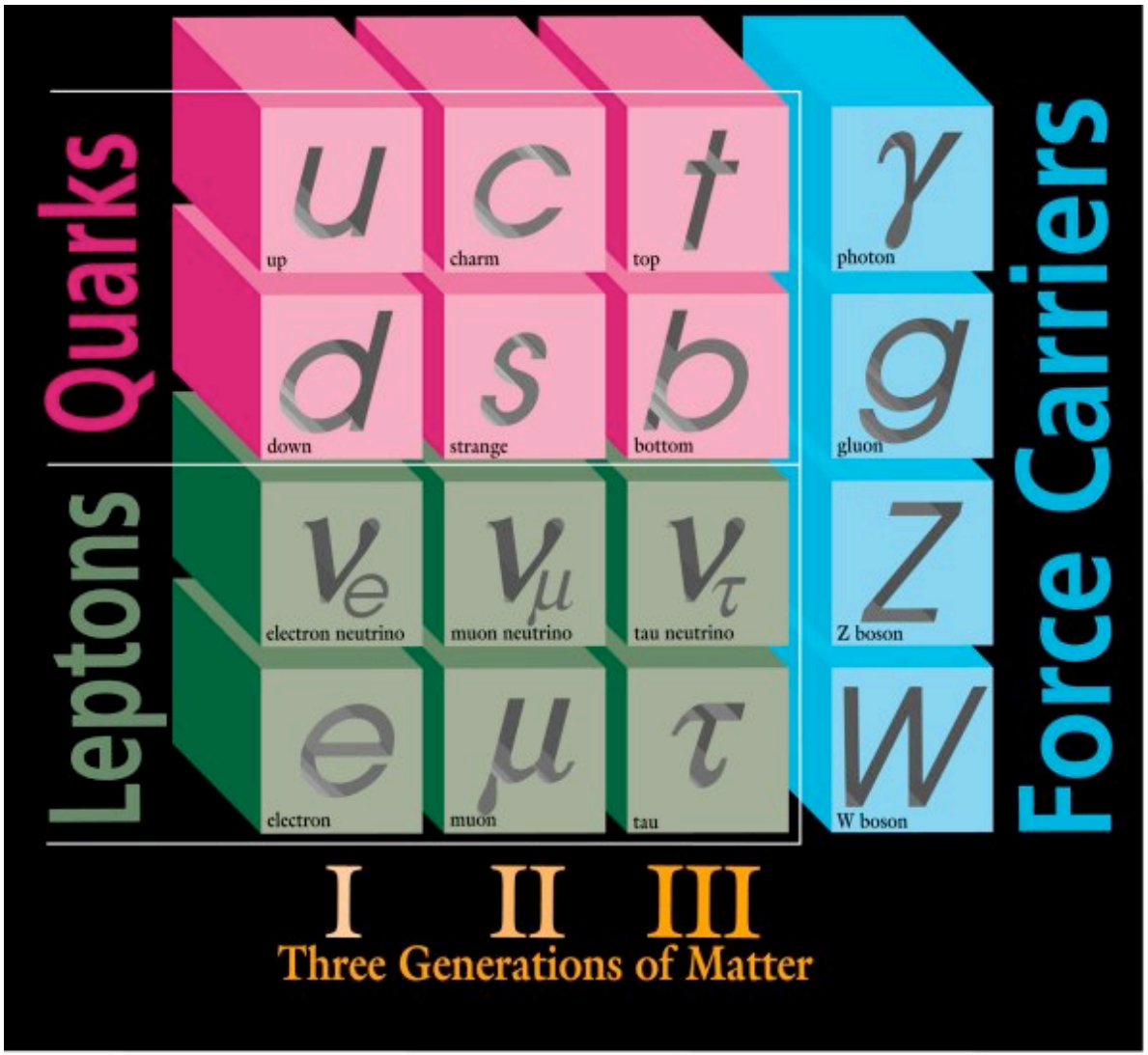
Overview

- Matter vs Antimatter
- B_s Oscillations
- Tools / Experimental Apparatus
- Data Analysis
- Interpreting the Data

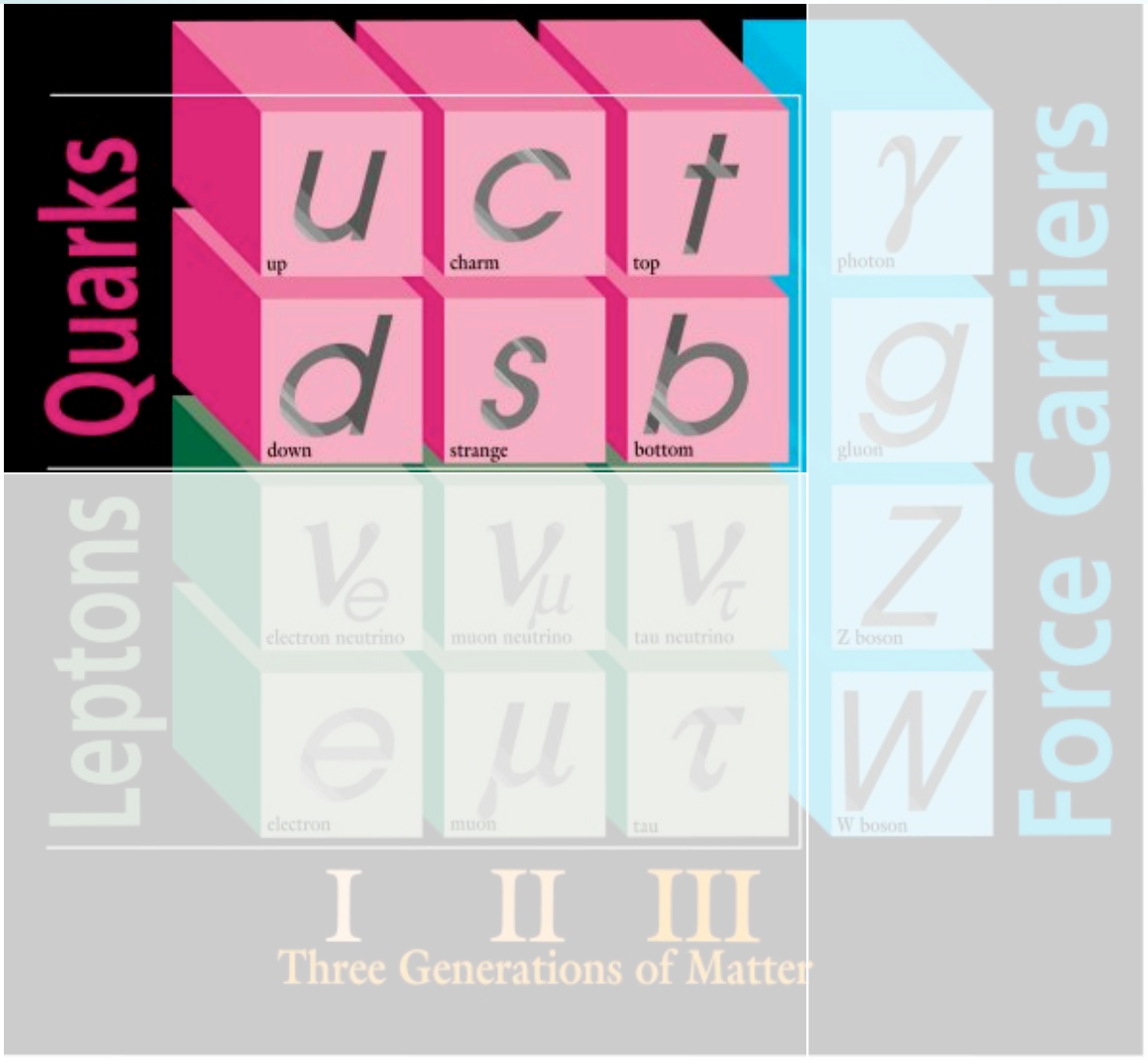
Matter in the Standard Model



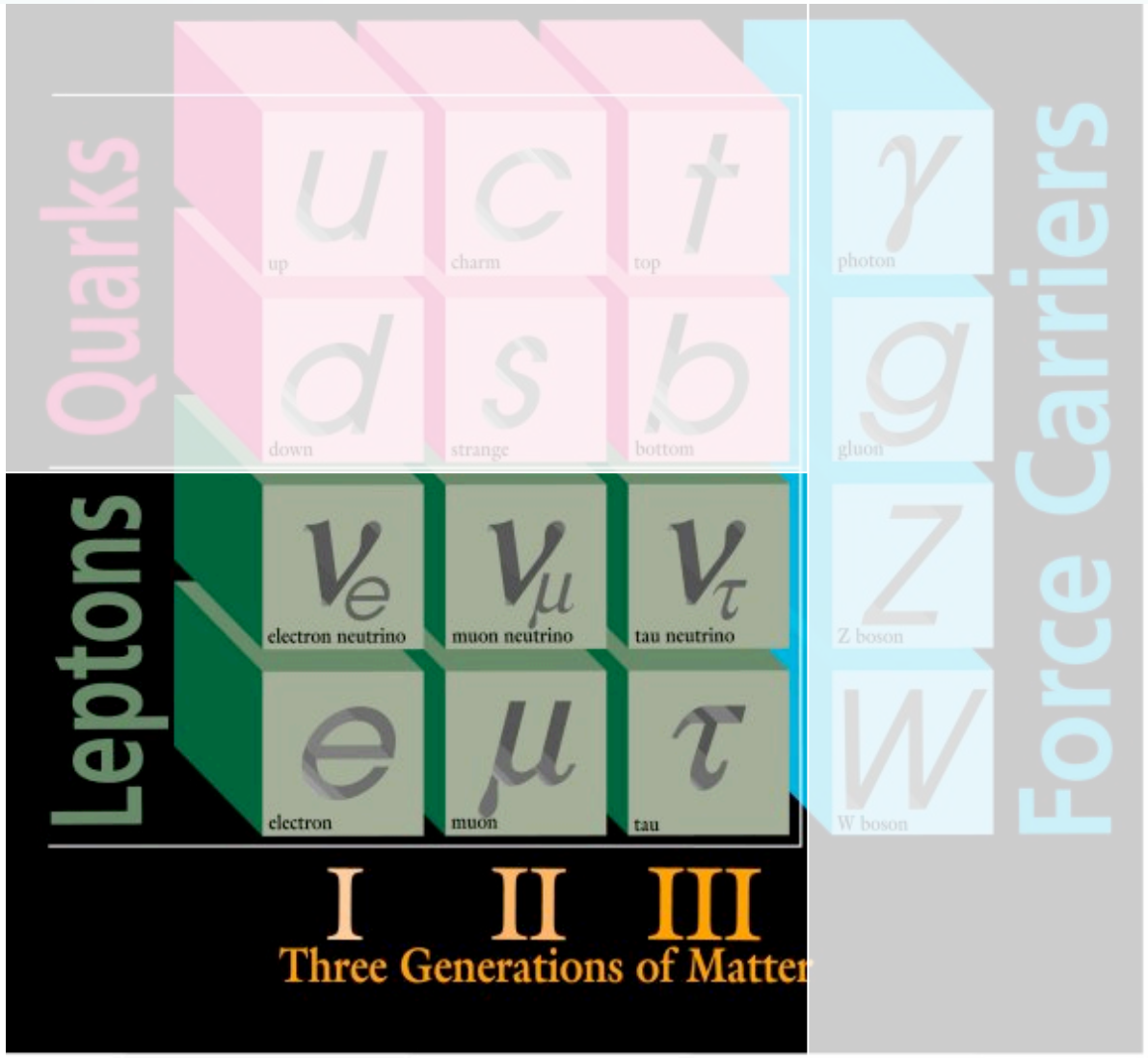
Matter in the Standard Model

+2/3

-1/3



Matter in the Standard Model



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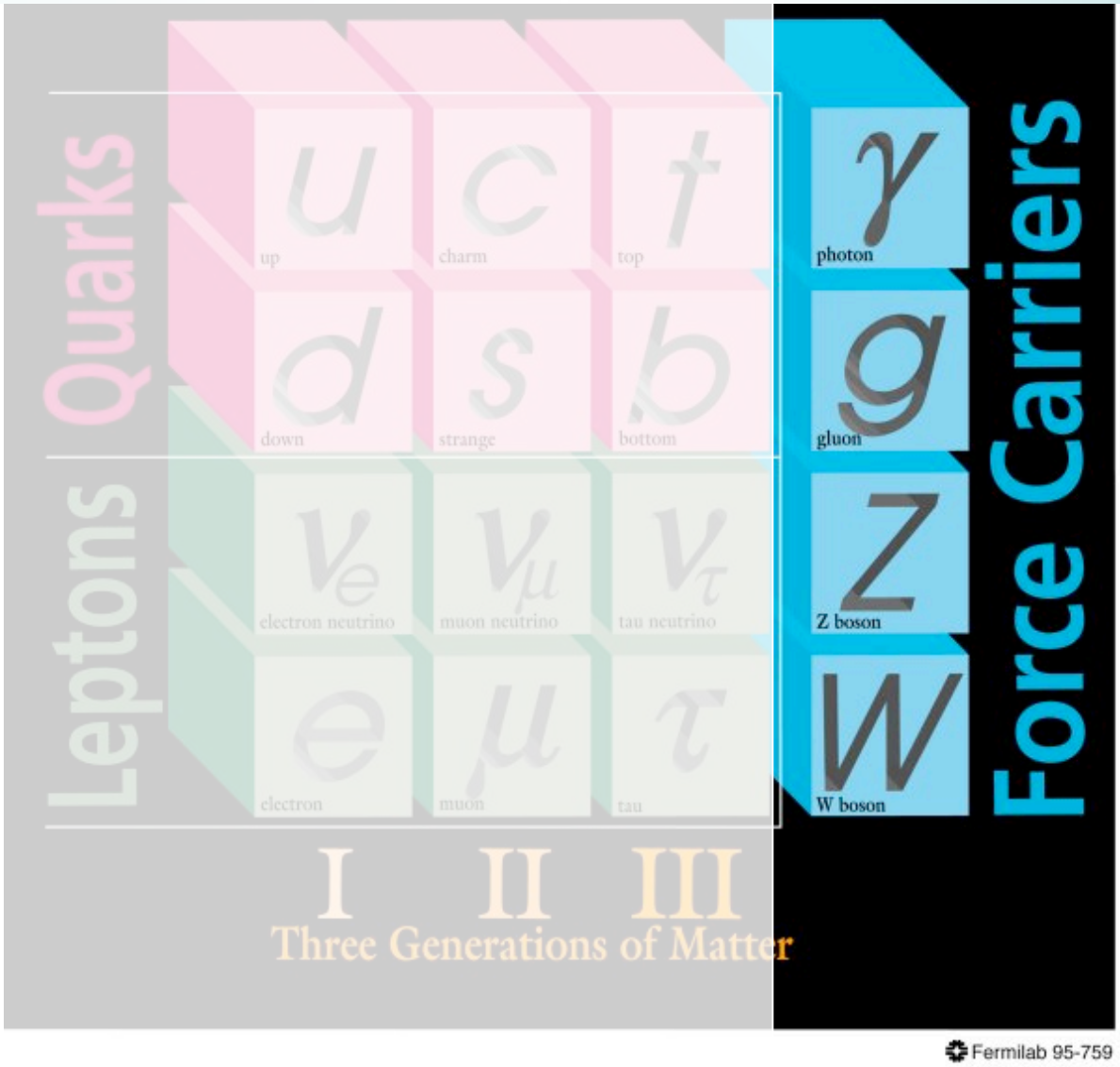
-1

Matter in the Standard Model



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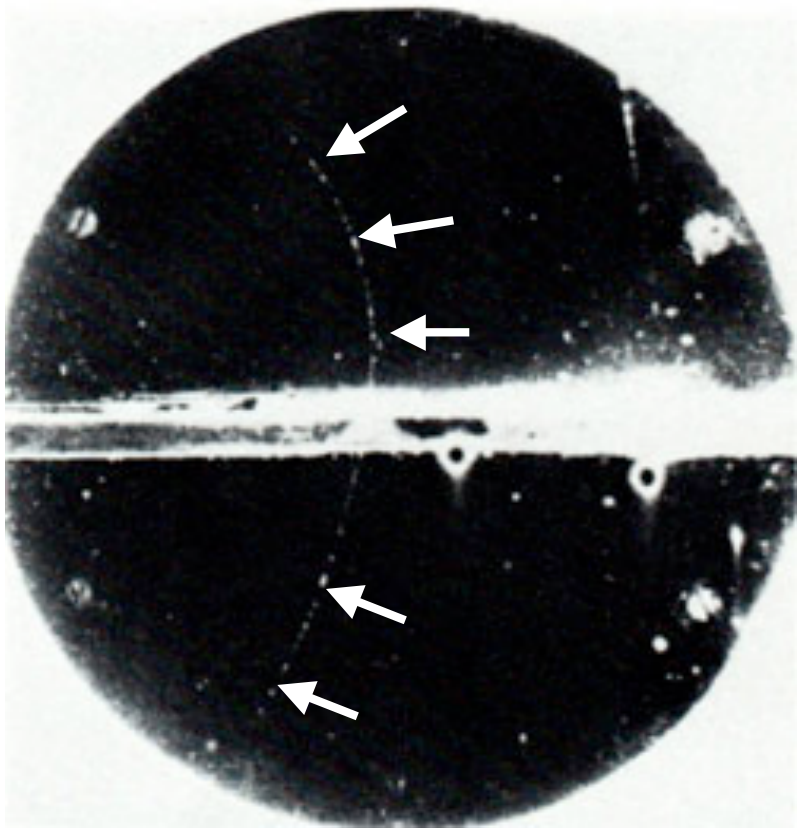
§1

Initial History of Antimatter

- 1928 Dirac predicts the positron (anti-electron)
- Antiparticles have same properties as particles, but opposite charge
- 1933 positron found by Carl Anderson

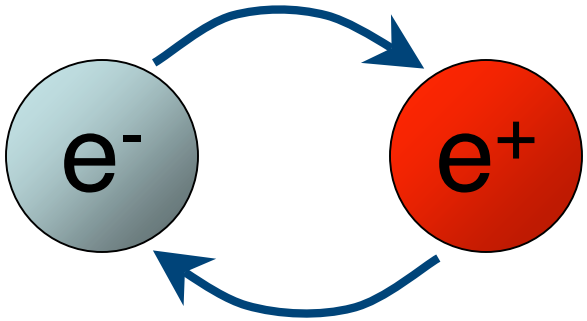


More History of Antimatter

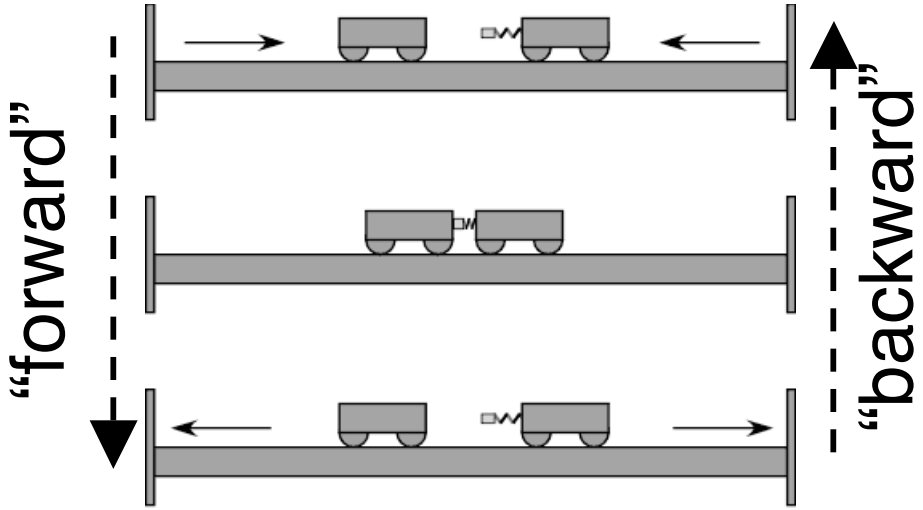
- 1955 anti-proton ! Serge, Chamberlain, et al.
- 1960 anti-neutron ! Cork, Piccione, et al.
- 1965 anti-deuteron found by two teams:
  - Leon Lederman et al. at BNL
  - Zichichi et al. at CERN
- anti-particles of most particles are found by now
- 1995 anti-atoms produced at CERN

Symmetries in Particle Physics

Charge (C)



Time (T)



Parity (P)
Spatial Inversion

Sakharov's Conditions

- Why is there more matter than anti-matter in the universe (baryon asymmetry)?
  - Baryon number must be violated
  - C and CP symmetries must be violated
  - Above violations take place while universe is out of thermal equilibrium

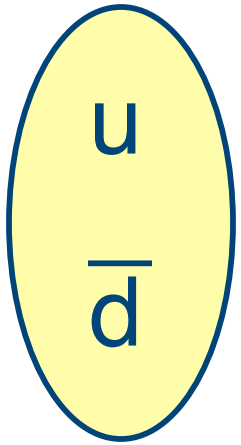
Broken Symmetries

Weak Interaction Processes

- P: asymmetric β ray spectrum in polarized Co^{60}
  - 1957 C.S. Wu et al.
- C: asymmetry of μ^+ and μ^- polarization in $\pi^{\S}$ decay
  - 1957 R.L. Garwin, L.M. Lederman, M. Weinreich
  - 1957 J. Friedman, V. Telegdi
- CP: in the neutral kaon system (K_S, K_L decays)
  - 1964 J.H. Christenson, J.W. Cronin, V.L. Fitch, R. Turlay
- CP: direct CP violation in neutral kaon system
  - 1999 KTeV collaboration
- T: rate difference for K^0 ! K^0 as function of time
  - CPLEAR and KTeV collaborations
- CP: in the neutral B meson system (B^0!$J/\psi K_S$) decays
  - 2000 BaBar and Belle collaborations

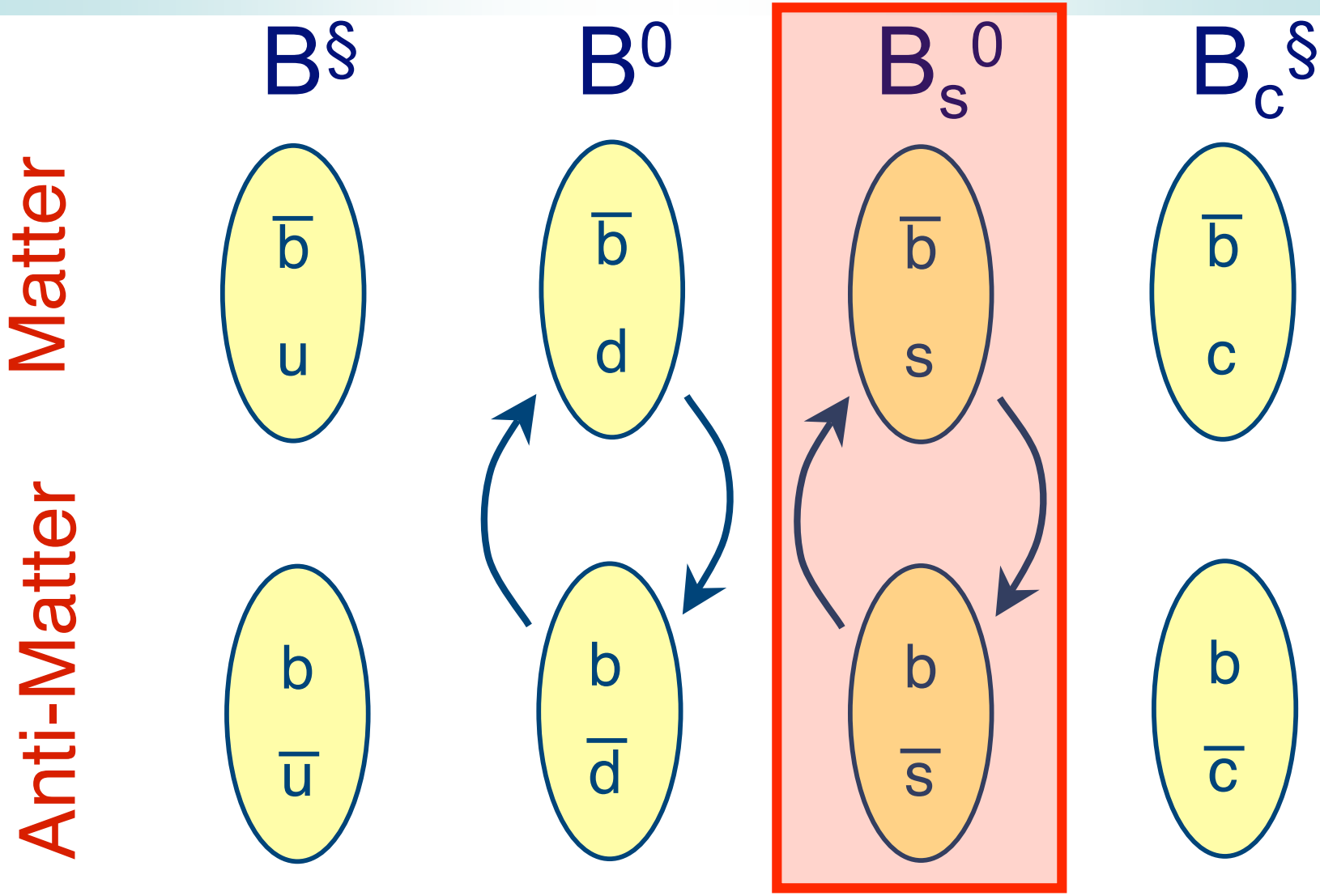
Matter – Antimatter Oscillations

- Meson: quark-antiquark bound state
- certain mesons can “swap” matter for antimatter quark without violating conservation laws
- this is the effect that we want to observe
- Matter-Antimatter oscillations established in Kaons, B^0 mesons..

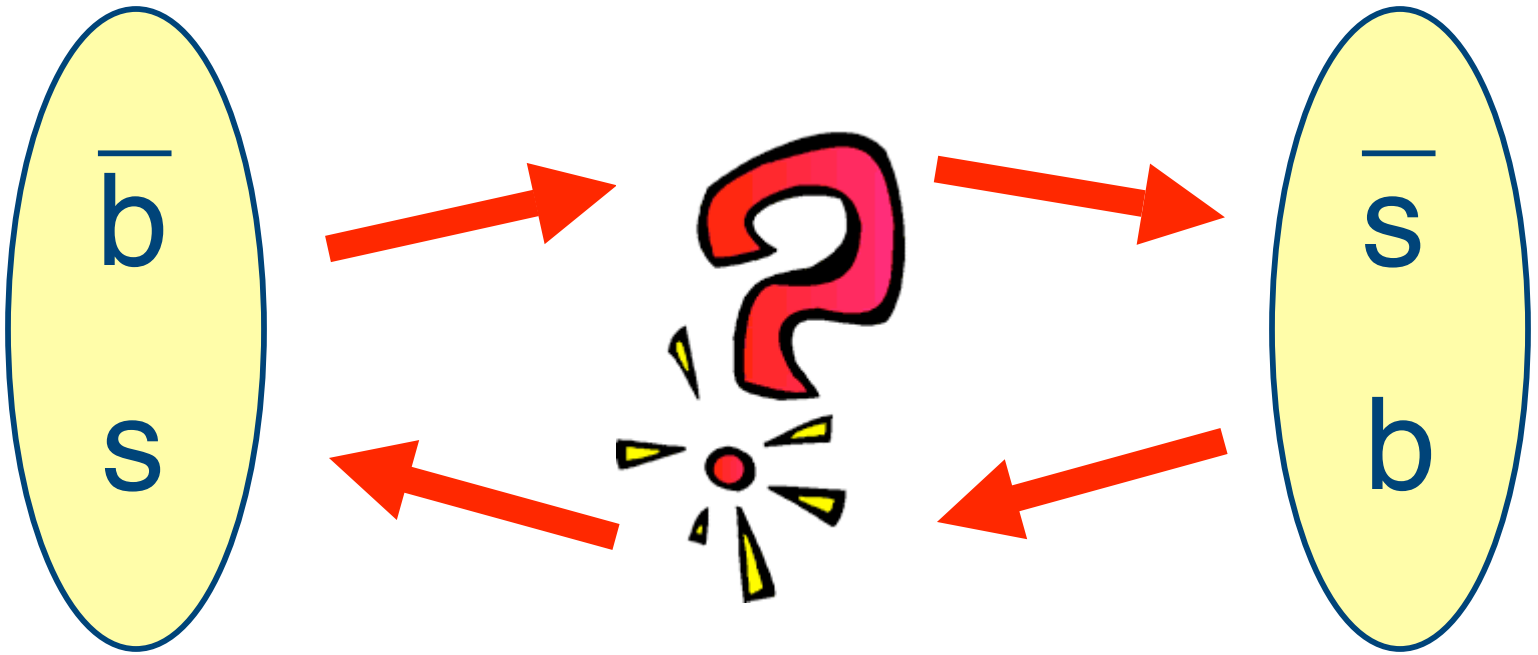


Pion (π^+)

B Mesons



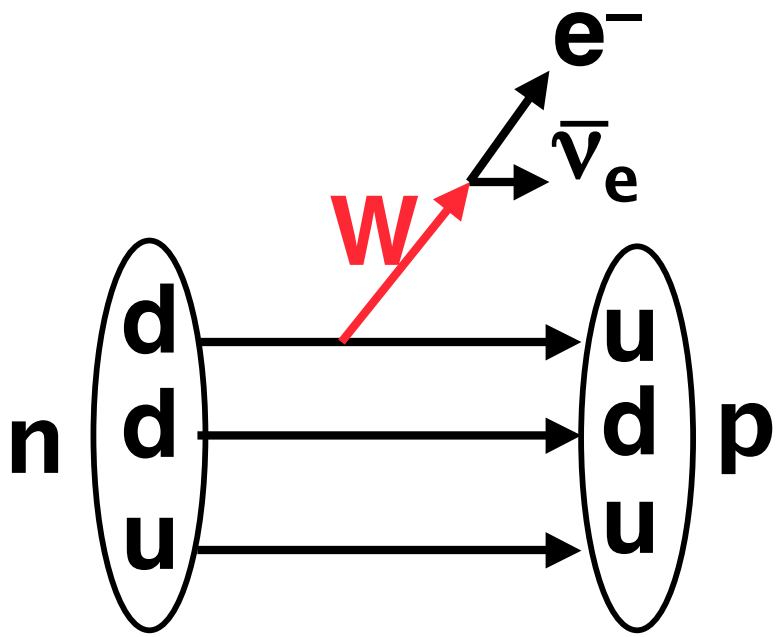
How can a B_s meson oscillate?

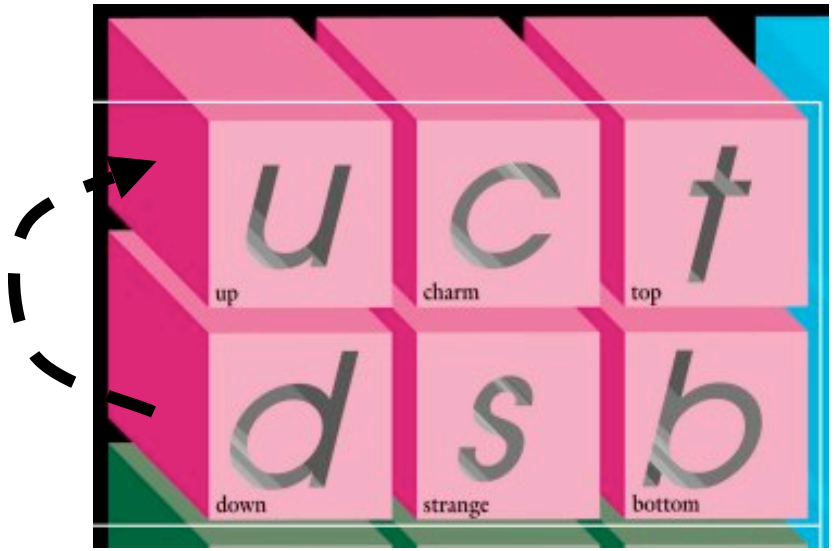


we need a process that can turn b ! s
(and vice versa)

Weak Interactions

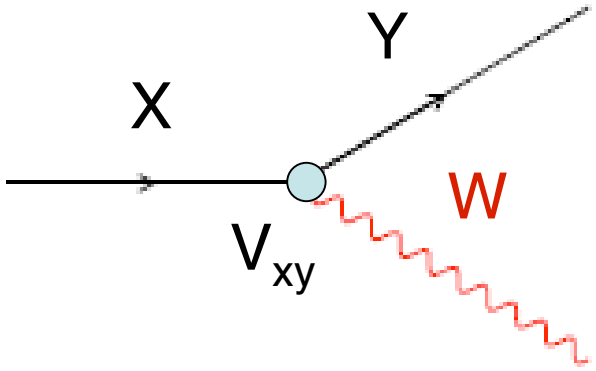
- weak interactions can change quark flavor!
- mediated by the W§ boson, example: n decay



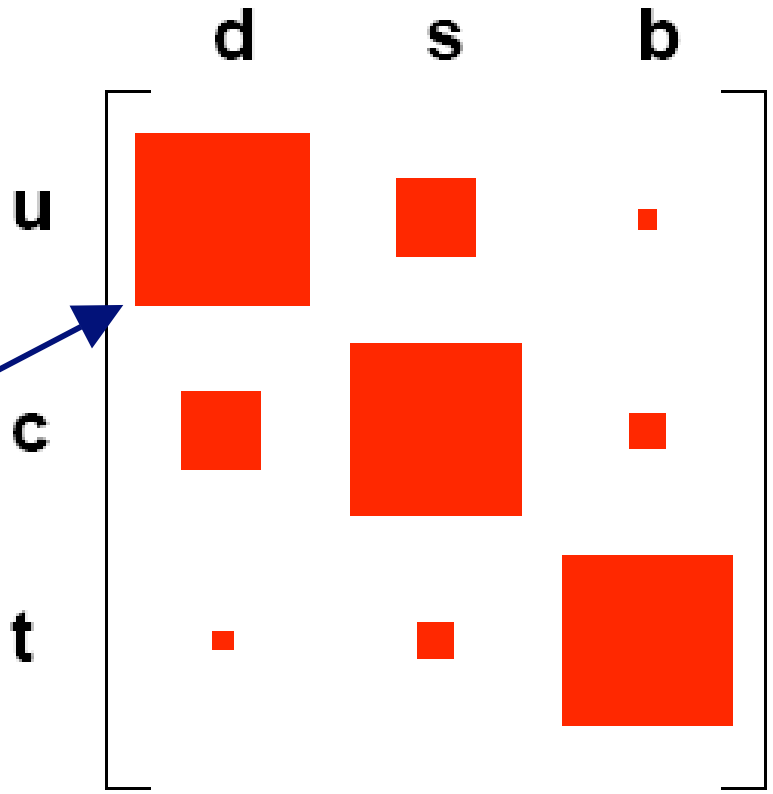


transition inside quark family

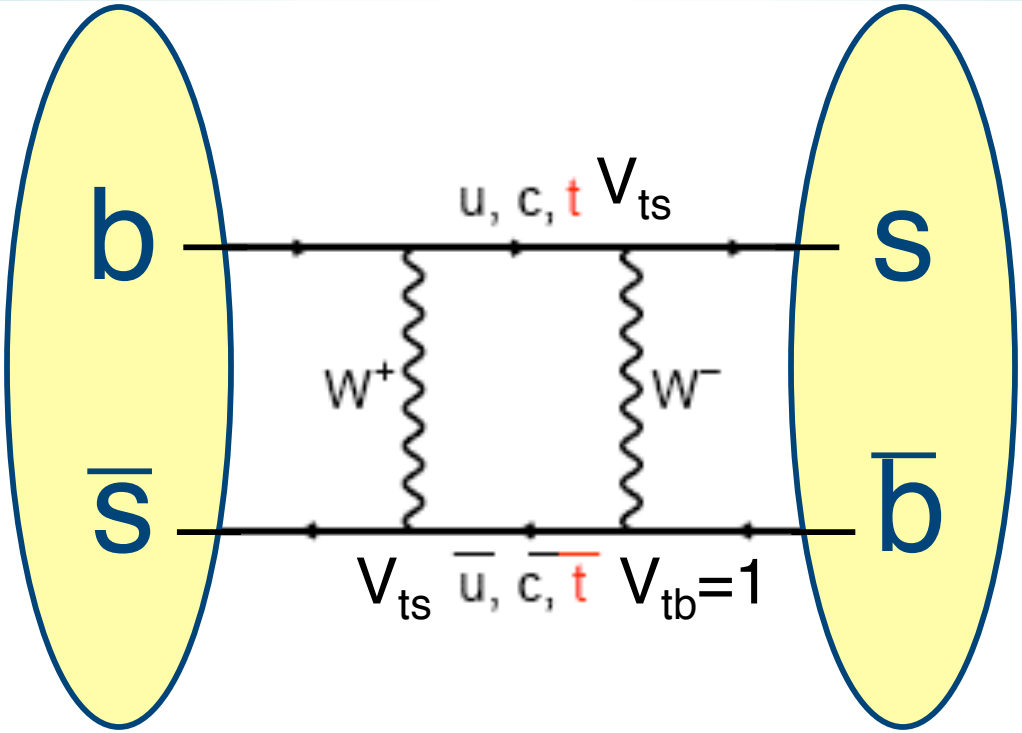
W§ Couplings to Quarks



- relative magnitudes of W – quark couplings
- diagonal elements – transitions inside family
- transitions between families supressed

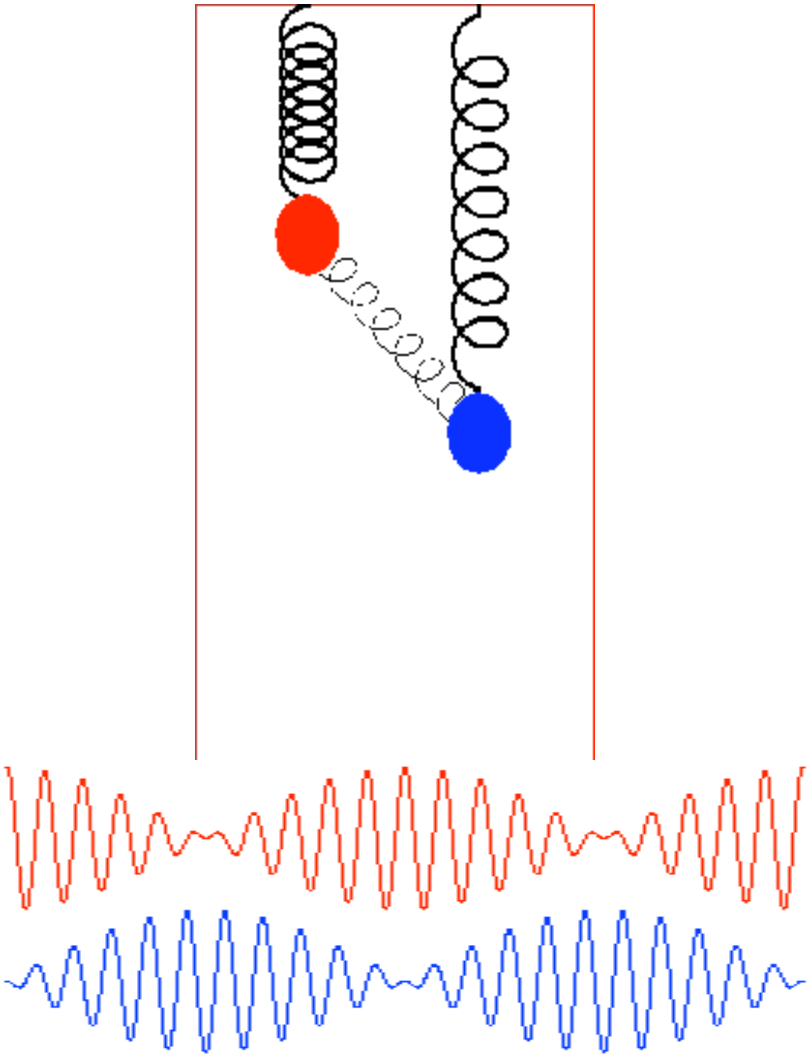


How a B_s meson oscillates

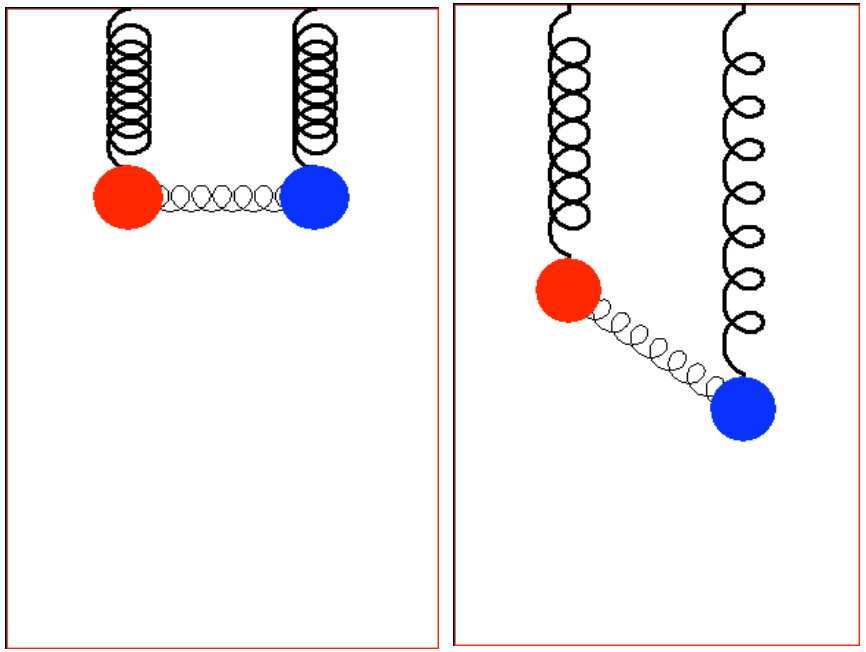


weak interaction simultaneously converts
b ! s, s ! b

A Classical Analogy



Eigenstates



Oscillation frequency ~ Coupling strength

The B_s Meson Also Decays!

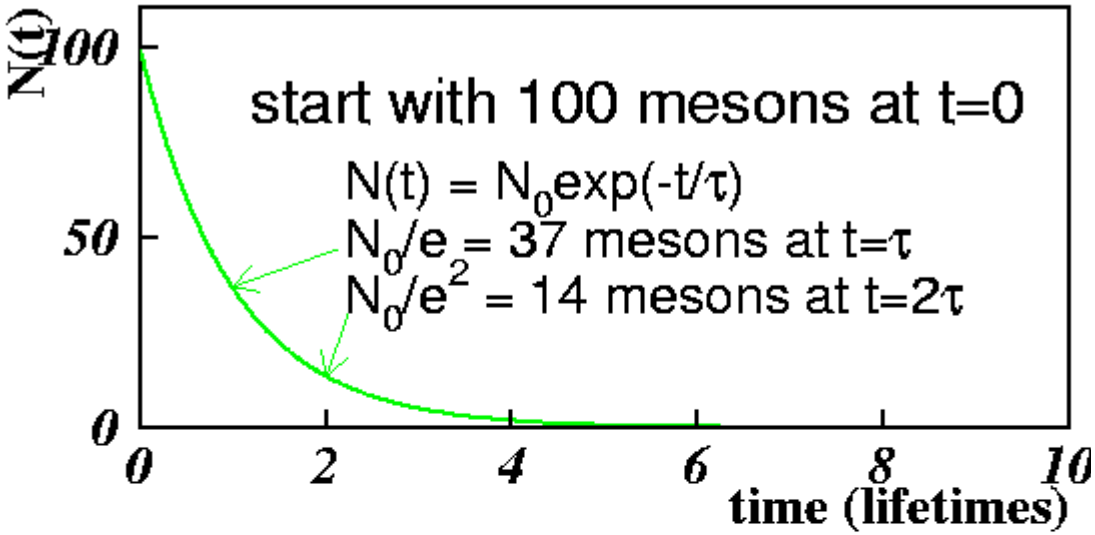
- b quark "lives" long

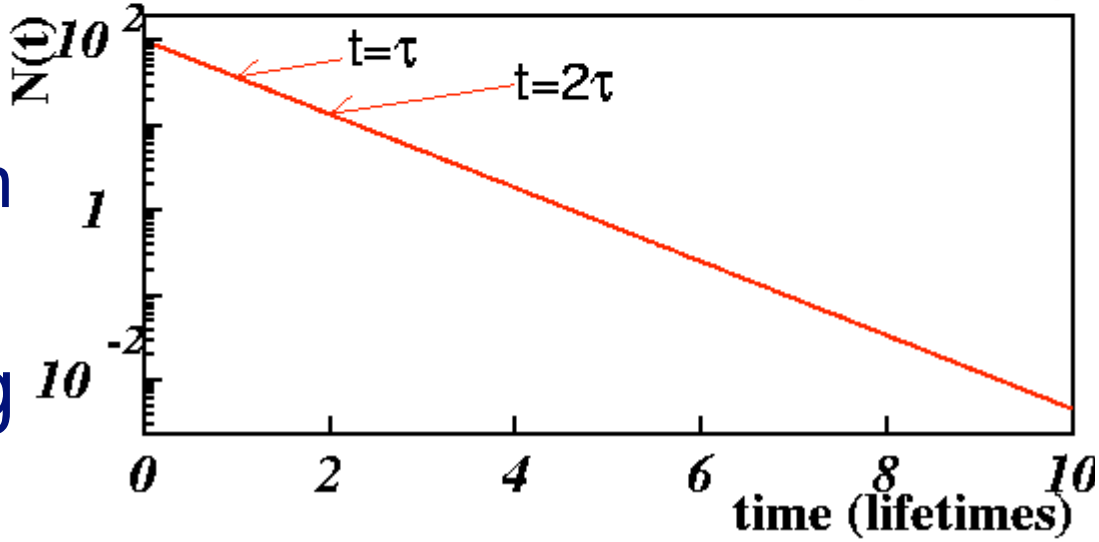
  $\tau_b = 1.5$ ps

  $c\tau_b = 450\ \mu m =$

  0.45 mm

- one lifetime (τ) is the point at which the parent sample is down by 1/e.
- important for mixing





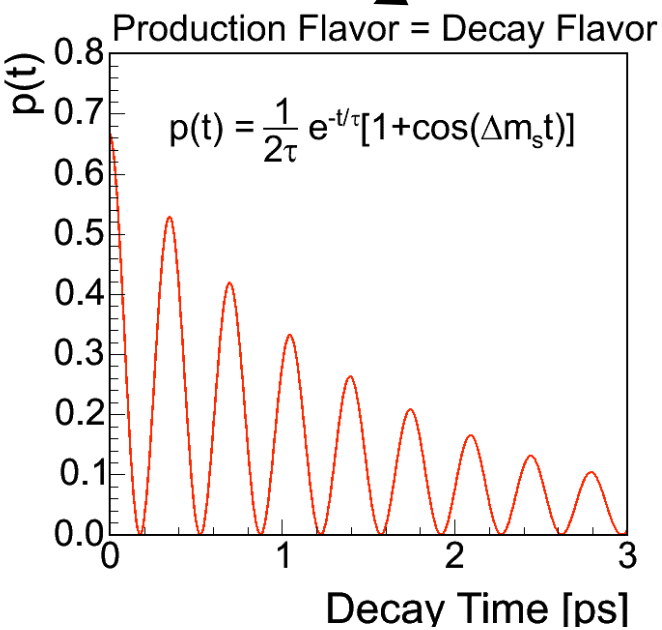
Use B_s decay time as stopwatch!

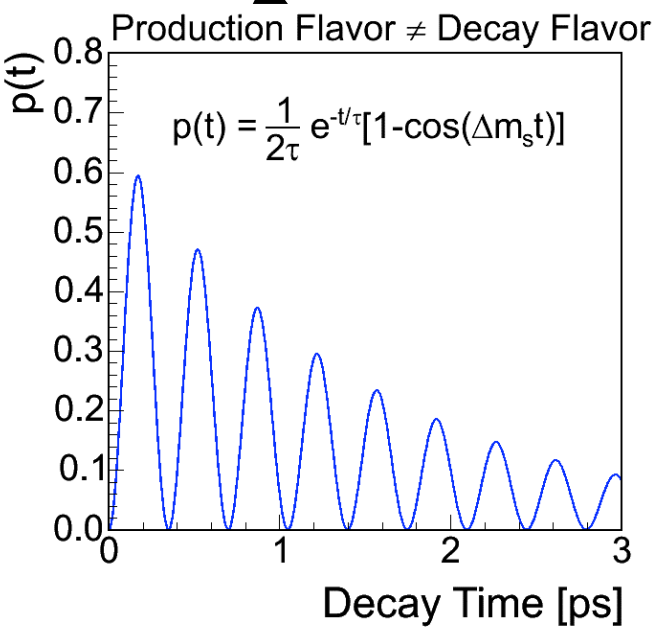
start with sample of pure B_s matter mesons

Decay as matter (un-mixed)

$\bar{b}$ s

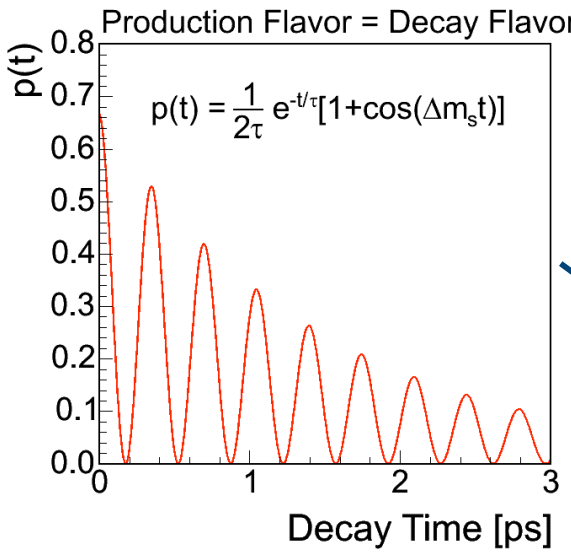
Decay as antimatter (mixed)



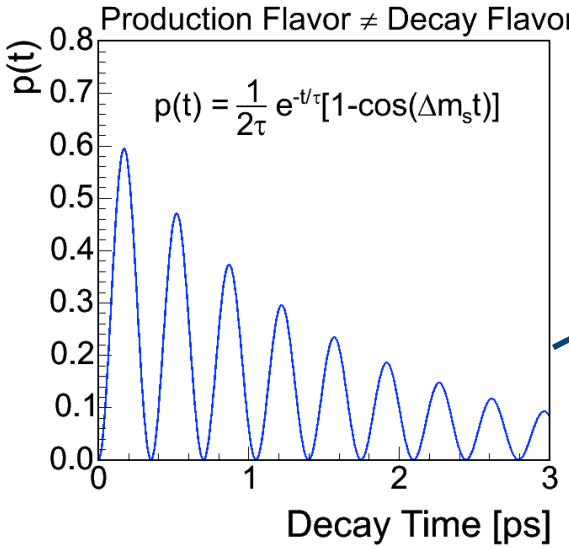


Asymmetry – a useful quantity

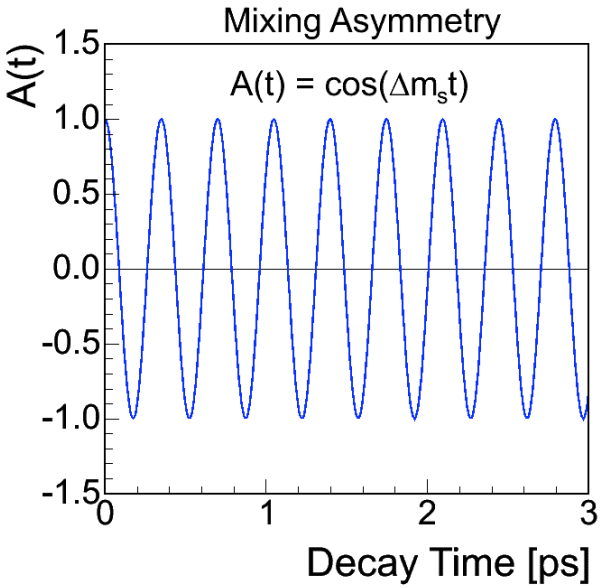
"Right Sign"



"Wrong Sign"



$$A(t) = \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}}$$



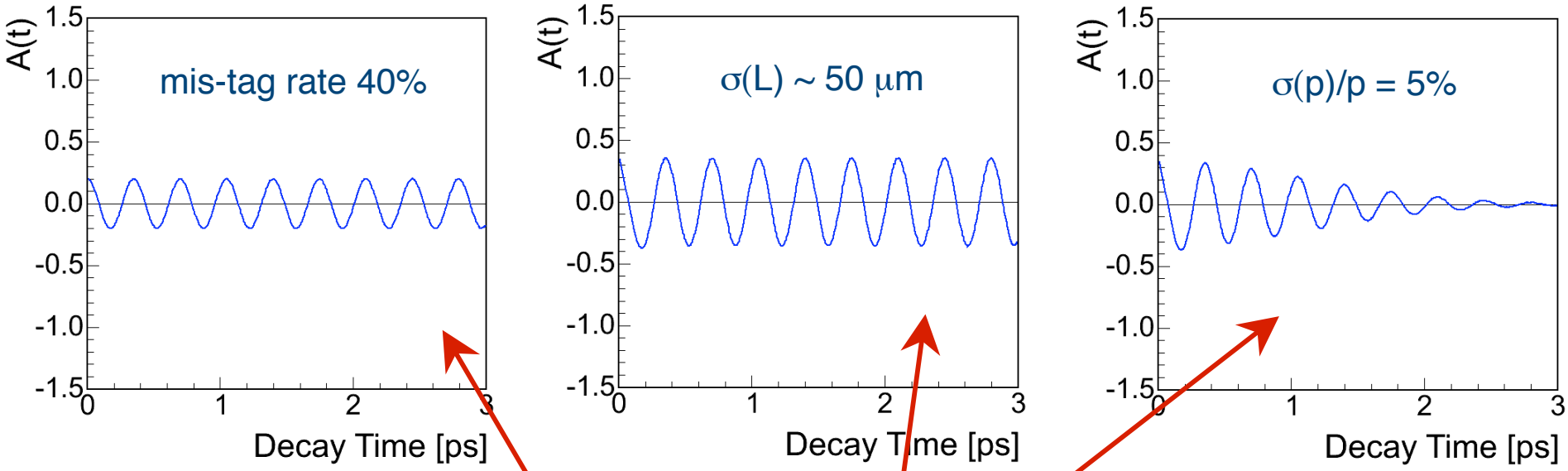
what about detector effects?

Realistic Detector Effects

flavor tagging power, background

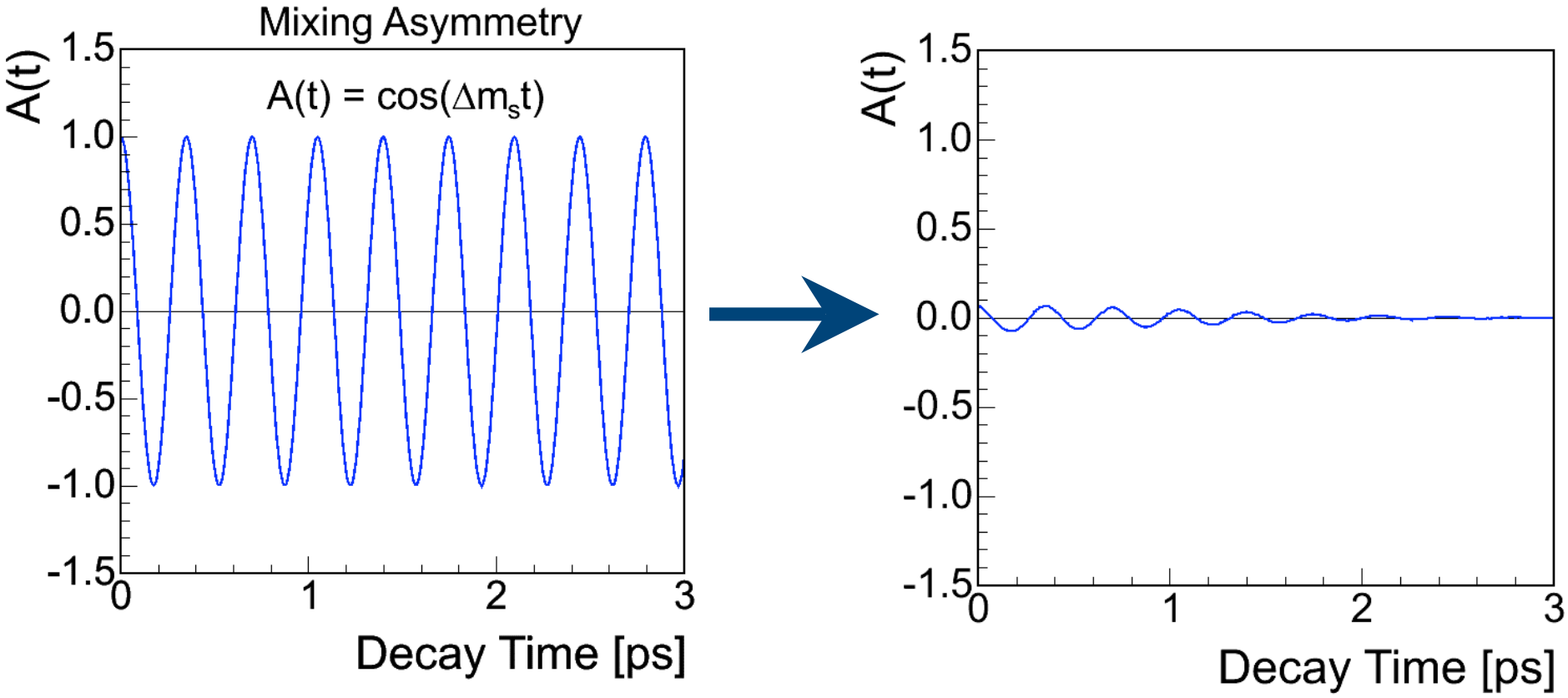
displacement resolution

momentum resolution



$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

All Effects Together



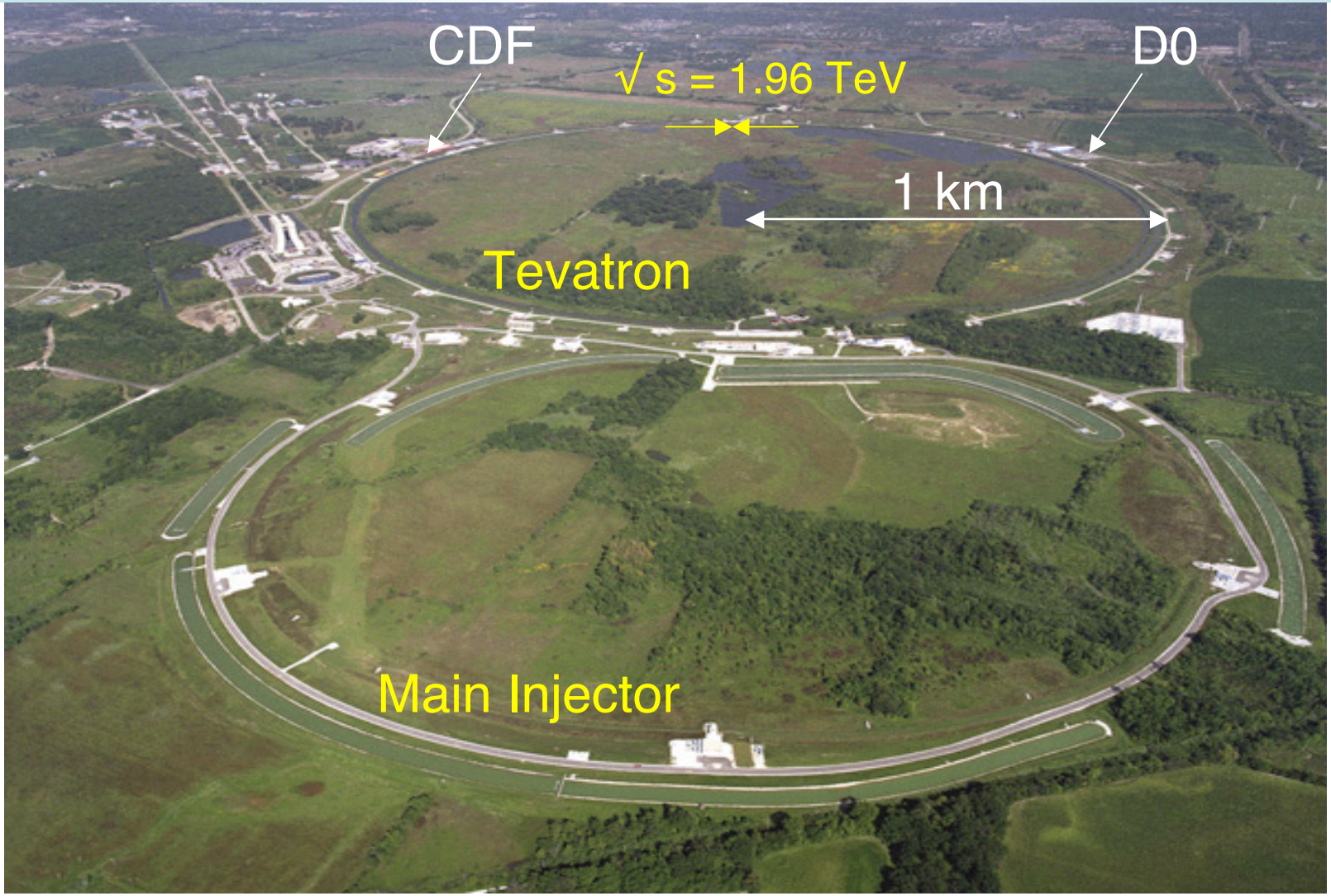
This is why previous measurements have not been able to observe B_s mixing!

Layout of the search for oscillations

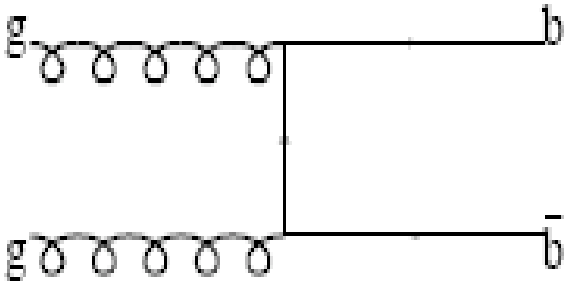
- produce lots of B_s meson decays
- reconstruct B_s meson decays
- was B_s produced as matter or antimatter ?
- did B_s decay as matter or antimatter ?
- measure B_s meson decay time
- look for oscillation pattern!

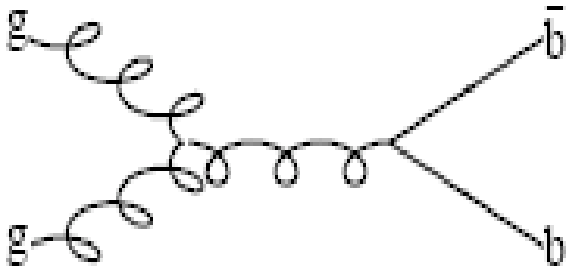
- let's see what tools we have available…

Tevatron Collider

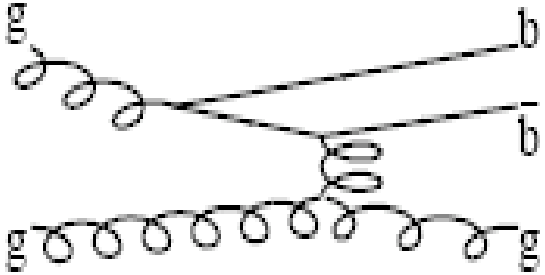


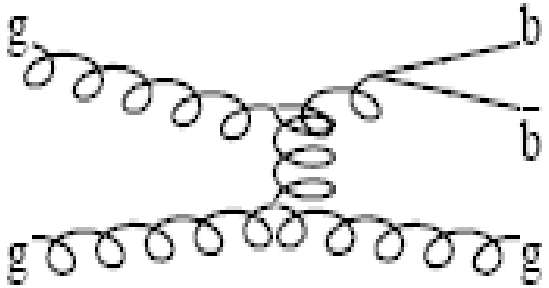
Production of b quarks





"flavor creation" "flavor creation"





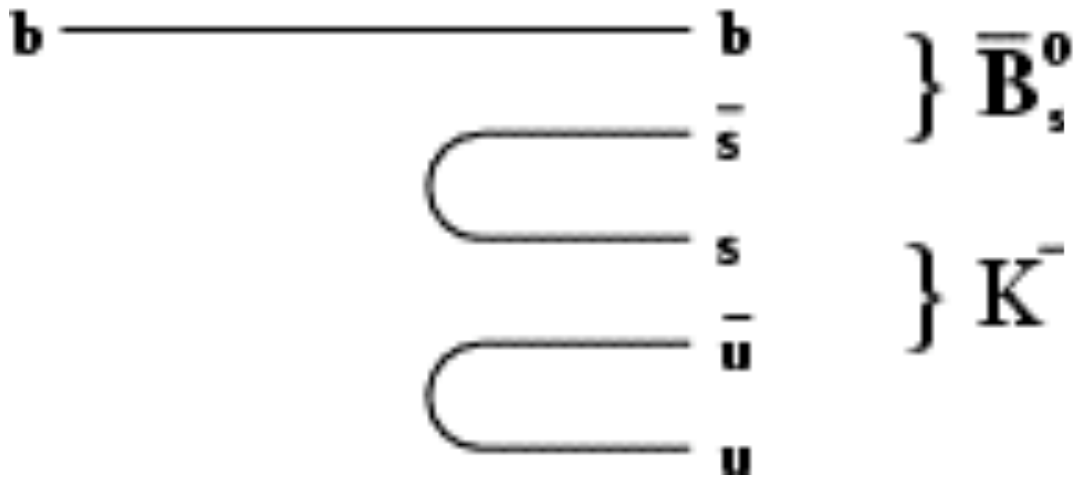
"flavor excitation" "gluon splitting"

- b quarks are produced in quark- antiquark pairs!

(this is useful for figuring out the production flavor)

From b quarks to B_s mesons

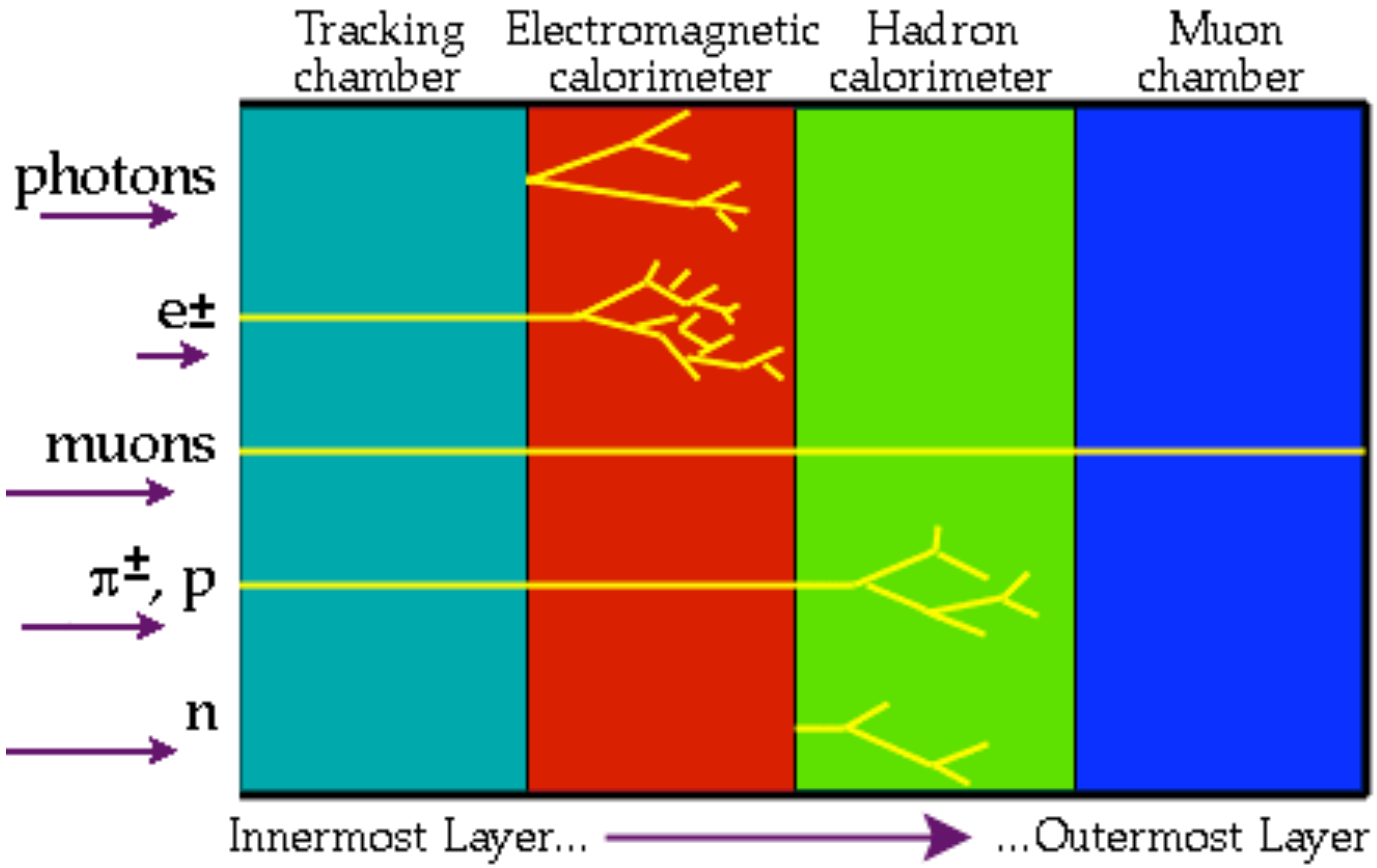
- bare b quarks don't exist, but form mesons



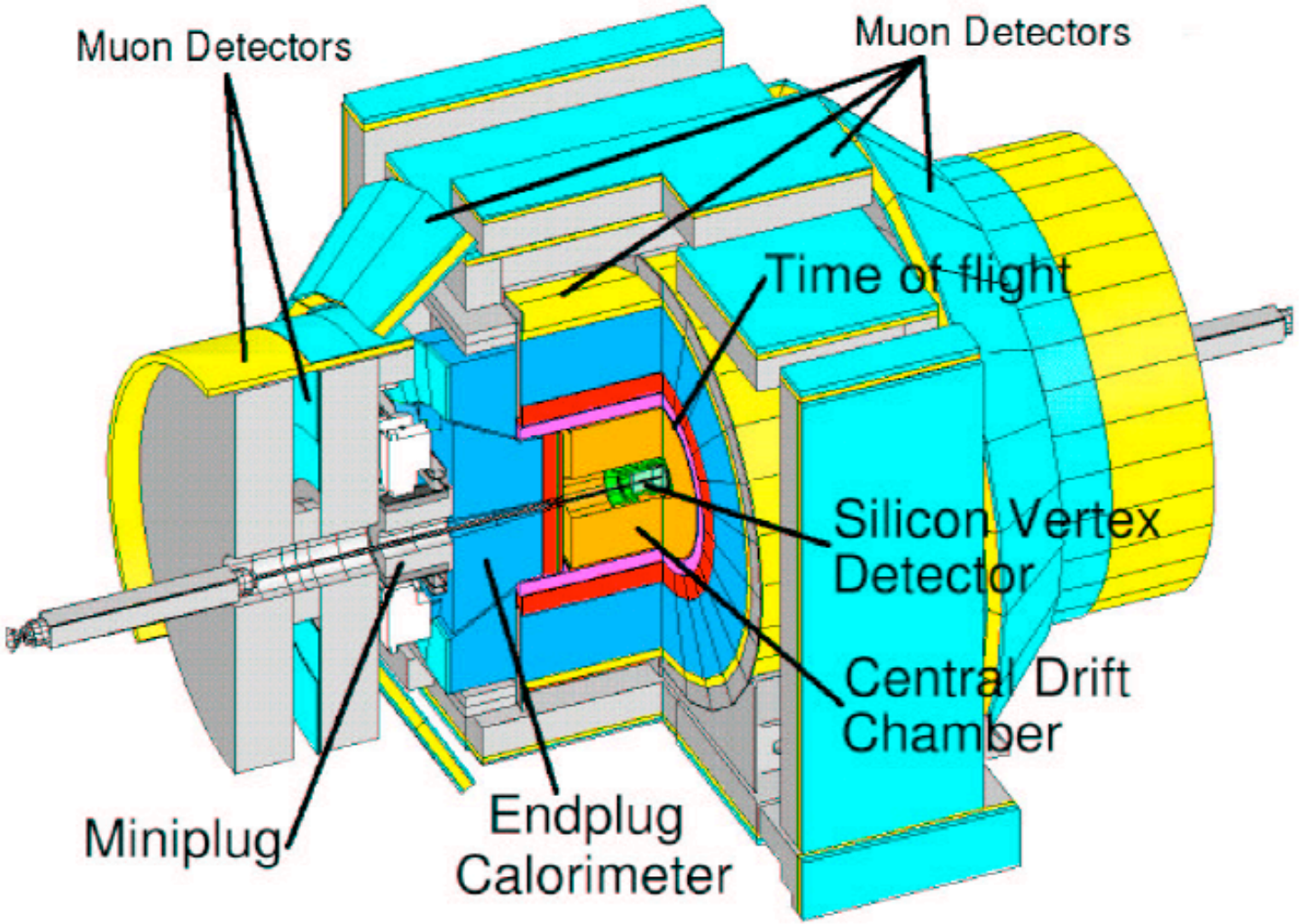
signature: a K^+ is likely to be found near a B_s !

(this is another way to tell the production flavor)

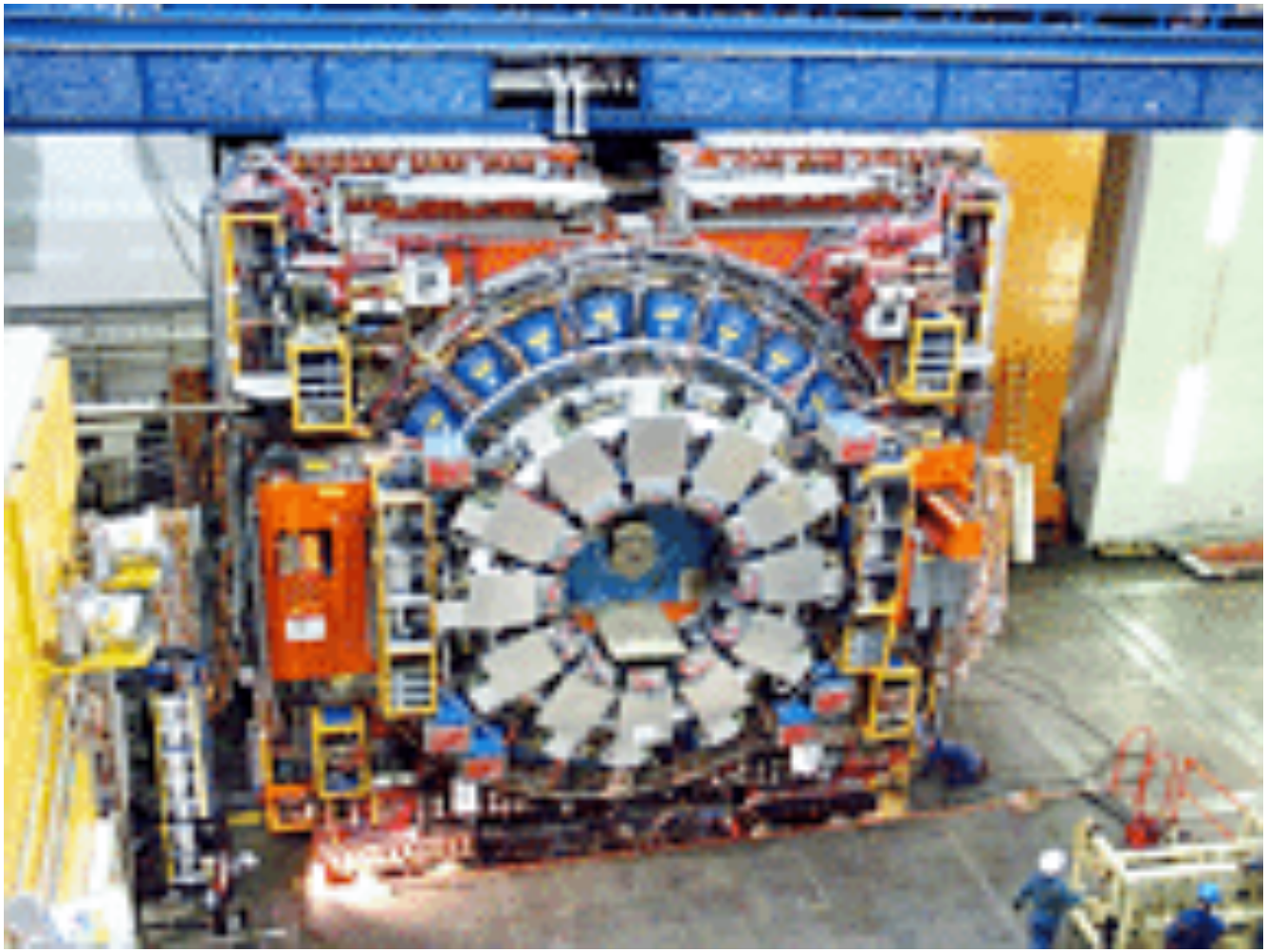
Multi-Purpose Detectors



CDF Detector



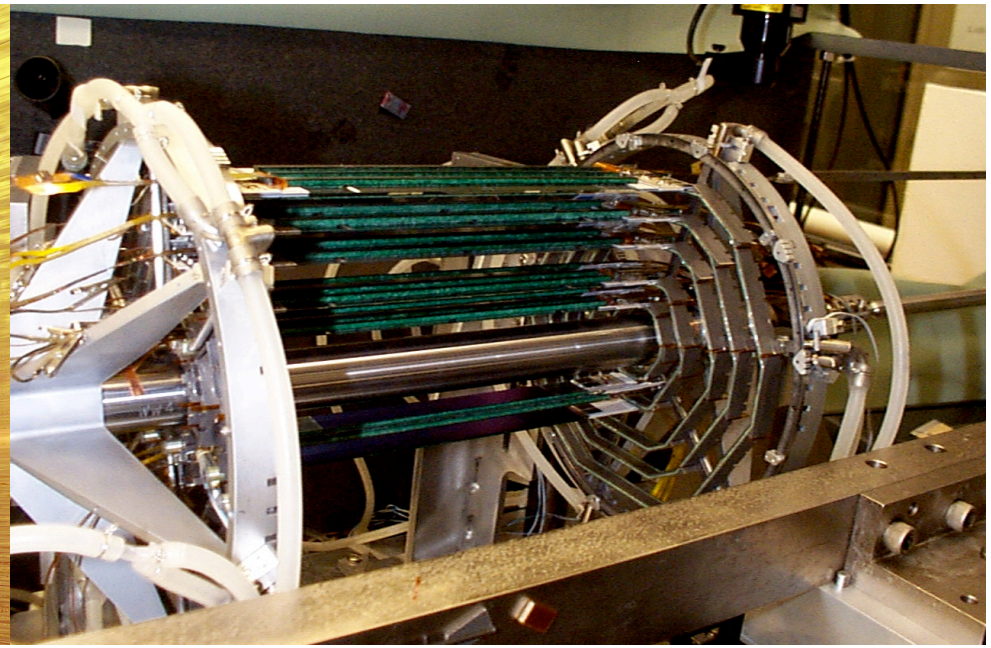
CDF Detector Rolling



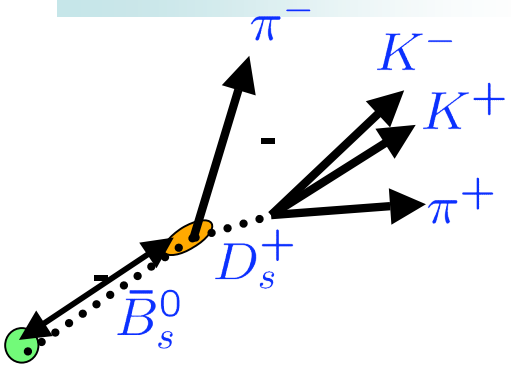
Tracking system

- immersed in 1.4 T solenoidal magnetic field
- charged particles follow helical trajectories

Drift Chamber (r~1.4 m) Silicon Tracker

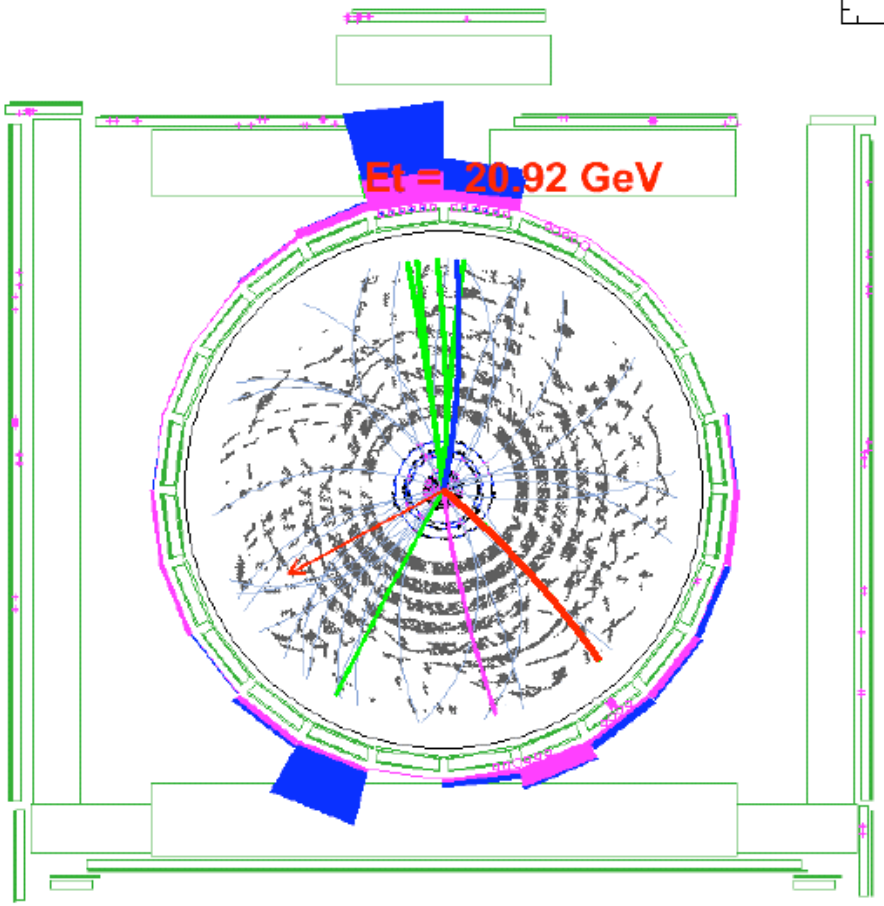


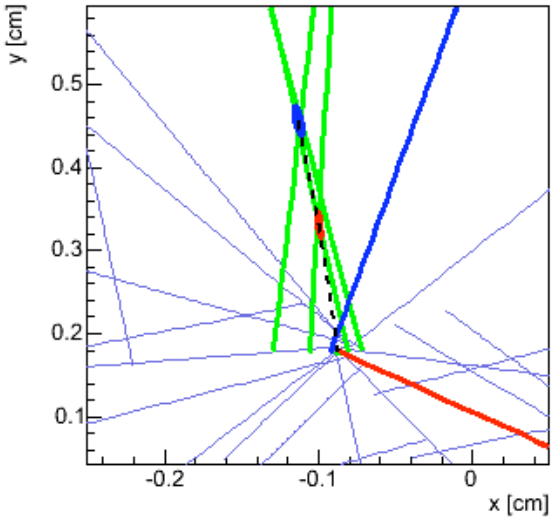
A B_s Meson Decay in CDF



production vertex
25μ m £ 25 μ m

$B_s ! D_s^- \pi^+$
$D_s^- ! \phi\ \pi^-$
ϕ ! K^+K^-

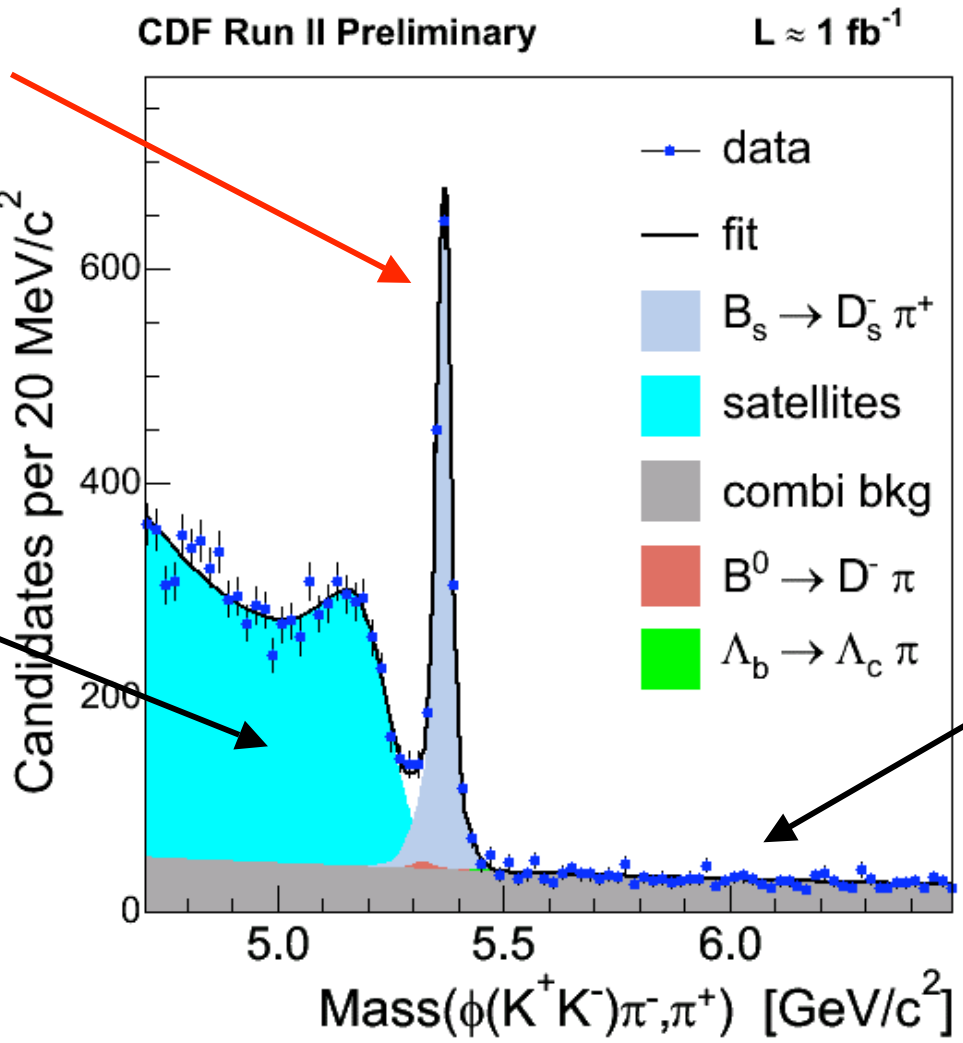




SSKT Track
Tag Muon
Other Track
Candidate Track
Beam Line
Primary Vertex
B Vertex
D Vertex
Path

Reconstructing B_s Decay Signals

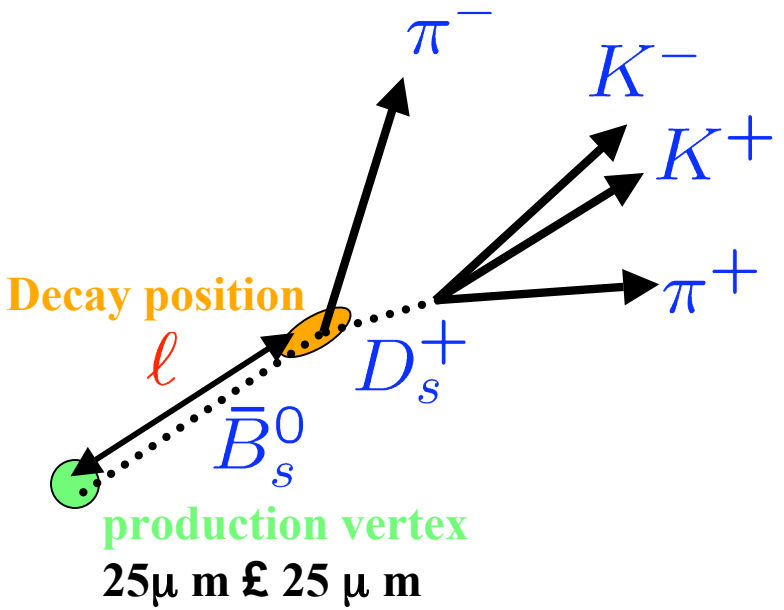
B_s signal

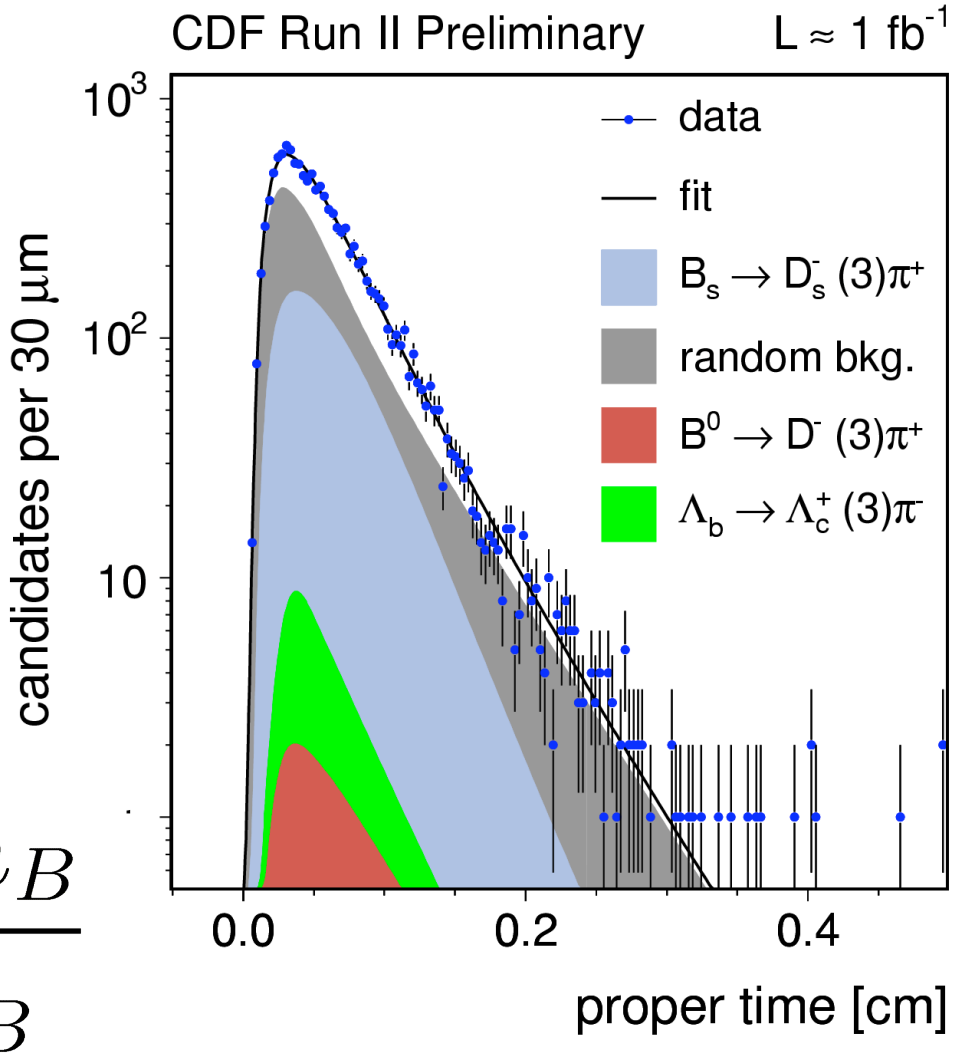


missing decay fragments

random track combinations

B_s Meson Decay Time

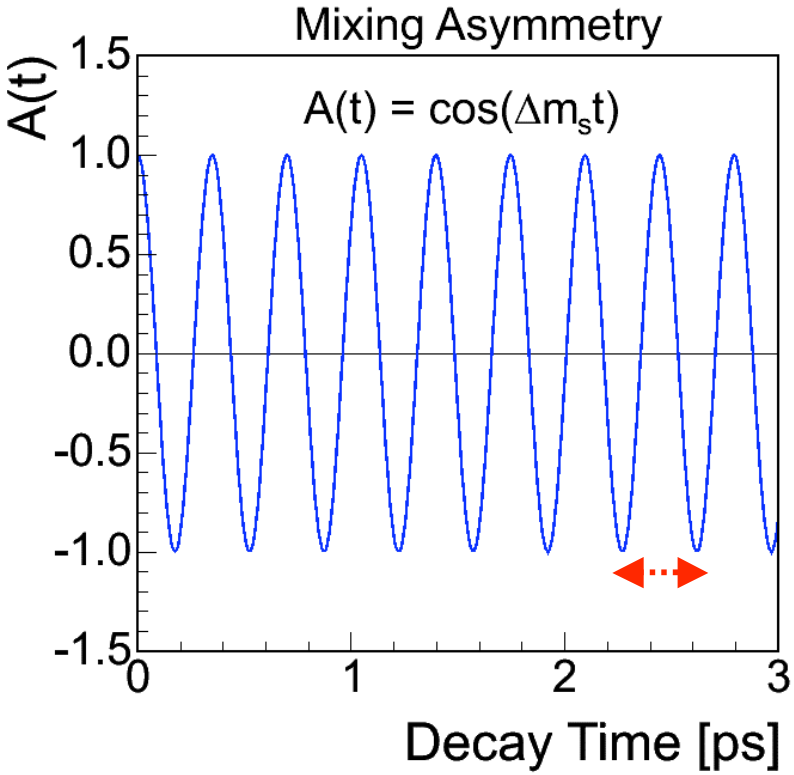




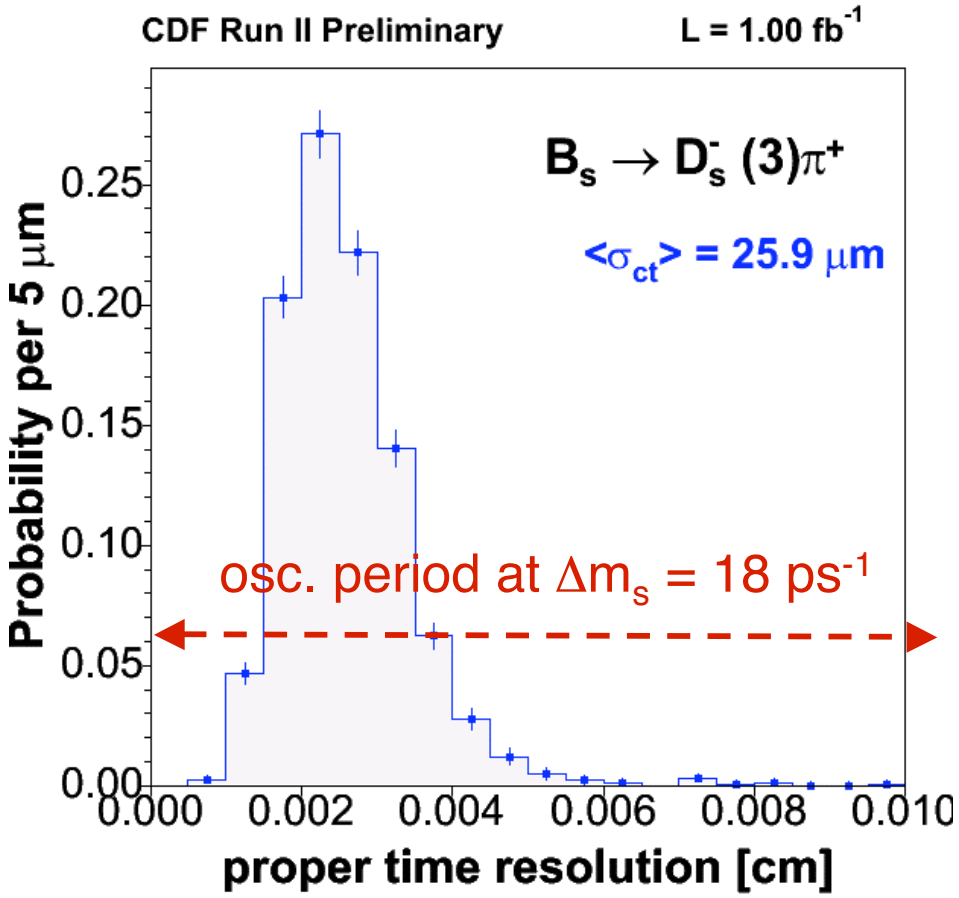
Decay time in B rest frame

$$t = \frac{\ell m_B}{p_B}$$

Decay Time Resolution

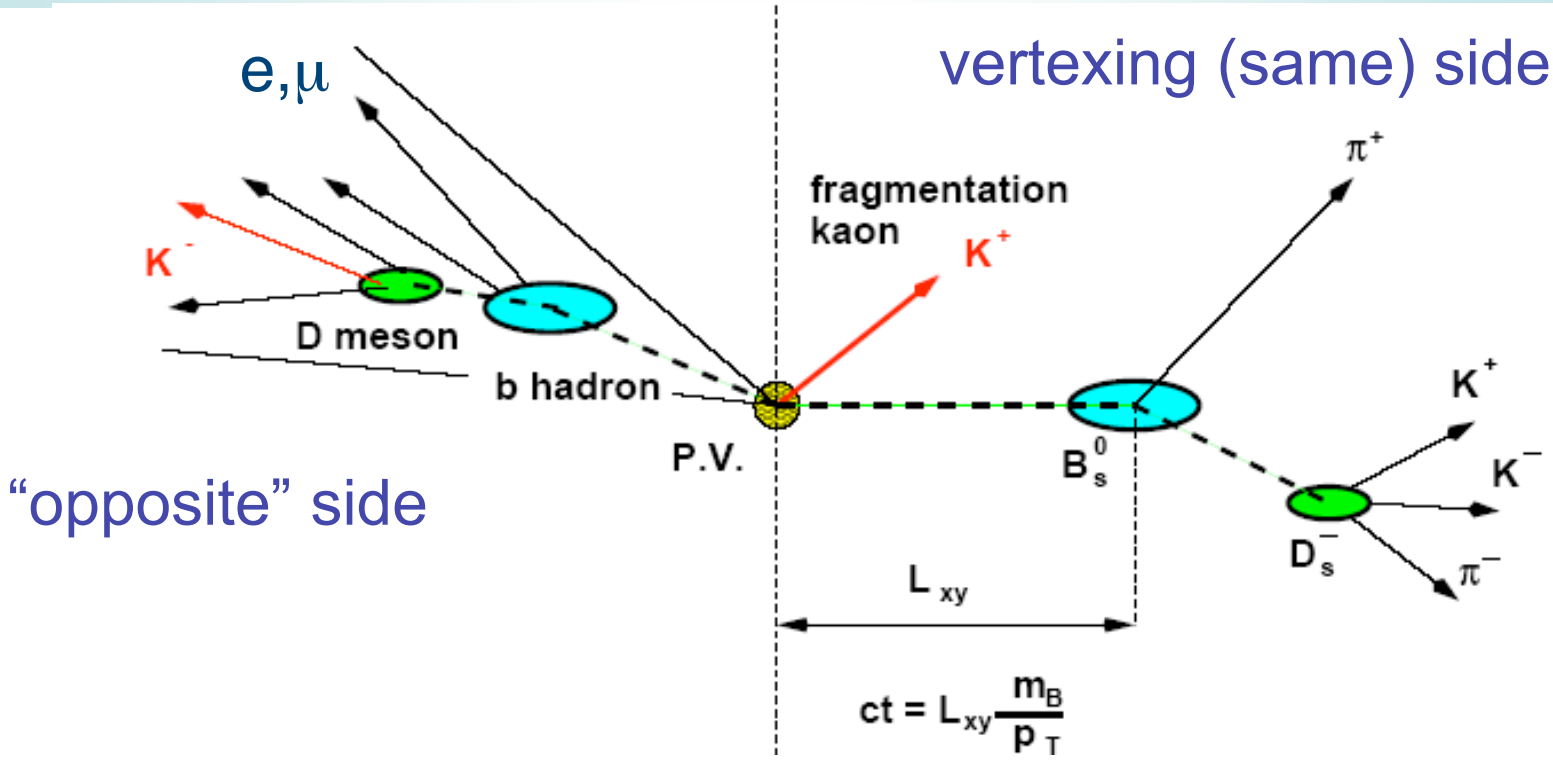


Avg resolution ~¼ period at $\Delta m_s = 18\ ps^{-1}$



superior decay time resolution gives CDF sensitivity at larger values of Δm_s than previous experiments

Was the B_s Produced as Matter?



- "opposite side" : look for other B meson in event, if it was matter, the B_s was antimatter!
- "same side": fragmentation remnants

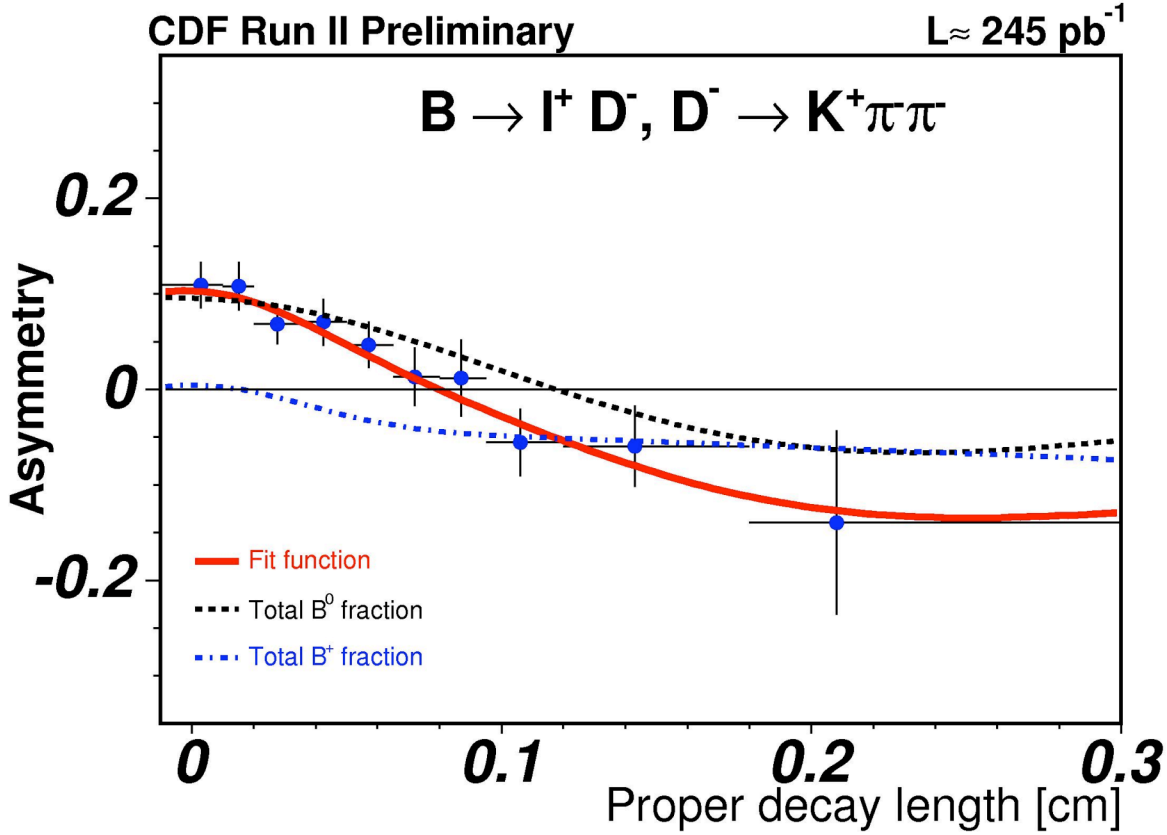
Ingredients for oscillation search

- ✓ produce lots of B_s meson decays
- ✓ reconstruct B_s meson decays
- ✓ was B_s produced as matter or antimatter ?
  - flavor tagging techniques
- ✓ did B_s decay as matter or antimatter ?
  - decay remnants tell us the decay flavor
- ✓ measure B_s meson decay time

- we have all the necessary ingredients
- look for oscillation pattern!

A Working Example: B^0 Oscillations

- The B^0 meson oscillates with Δm ¼ 0.5 ps^{-1}



- Search for mixing ! tool that scans frequencies

Fourier Transform of Asymmetry

$$\mathcal{A}(\Delta m) = \int_0^{T_{max}} \mathcal{A}(t)\cos(\Delta m \cdot t)dt$$

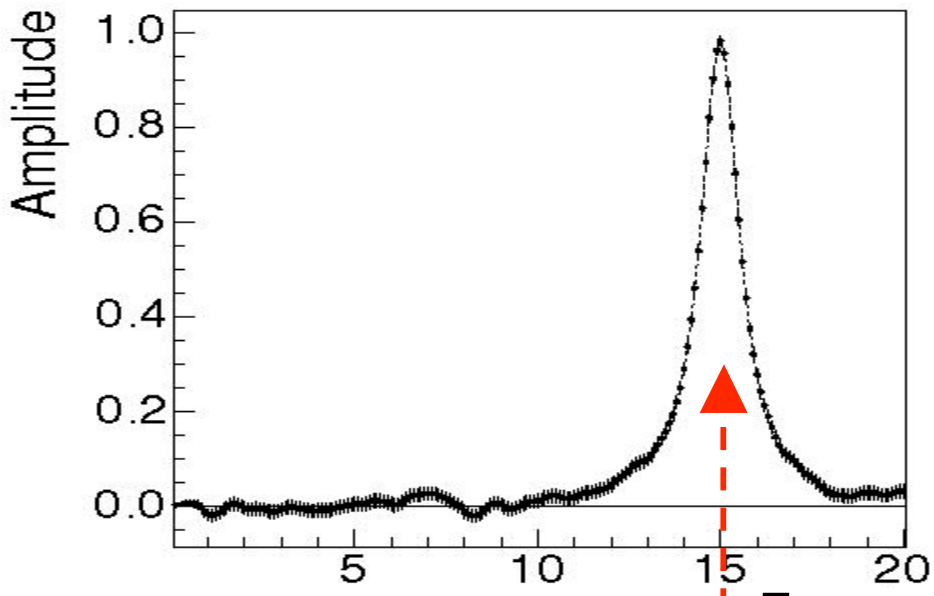
- Useful properties:

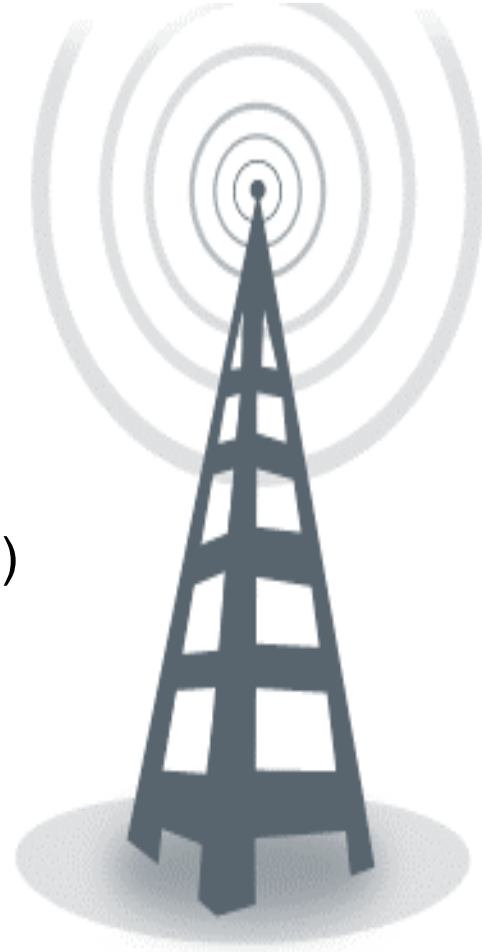
A(Δm) ¼ 0 if no mixing at Δm

A(Δm) ¼ 1 if mixing at Δm

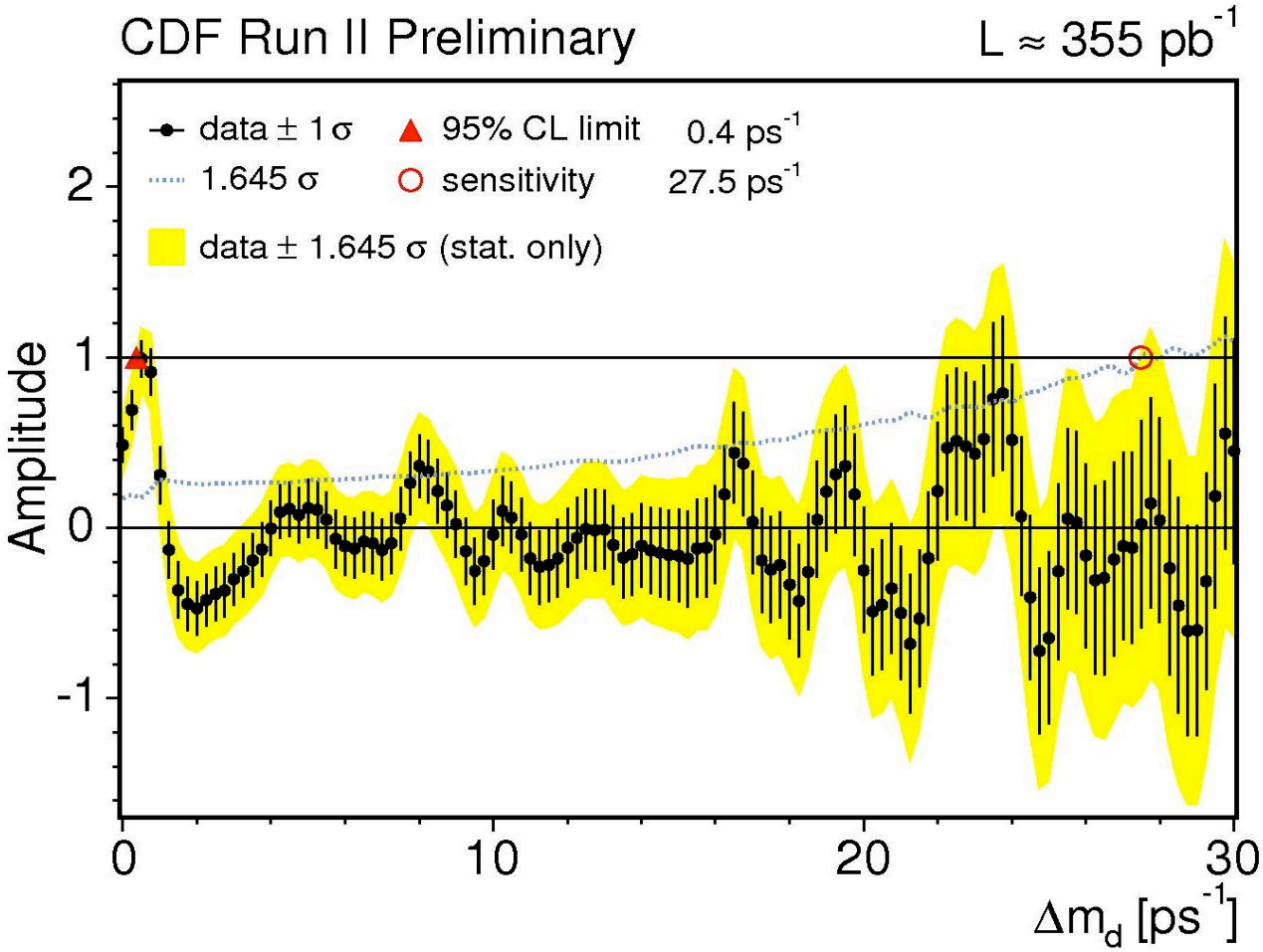
"calibrated for detector effects"

Amplitude “Scanning”

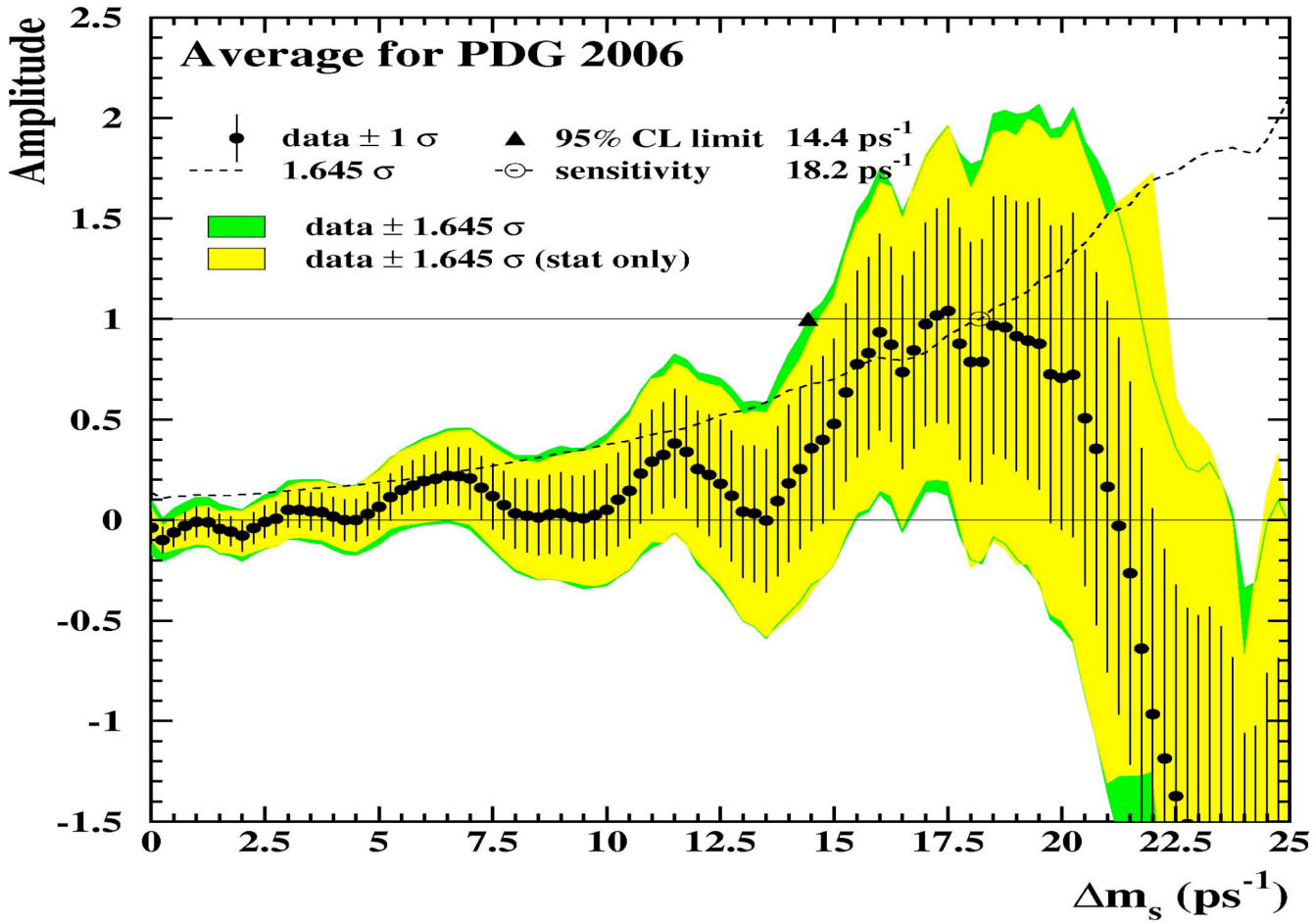




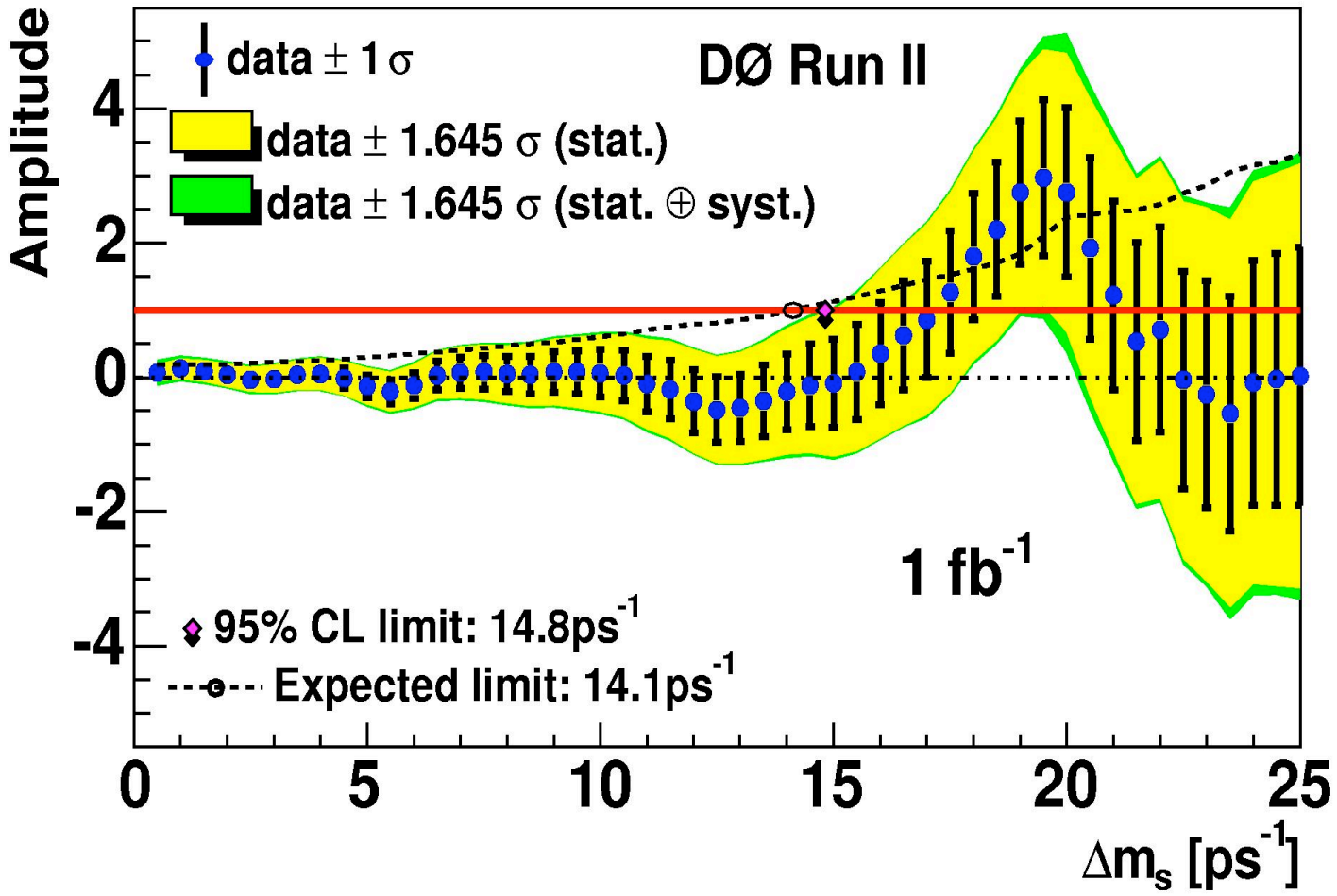
Amplitude Scan: B^0 Mixing



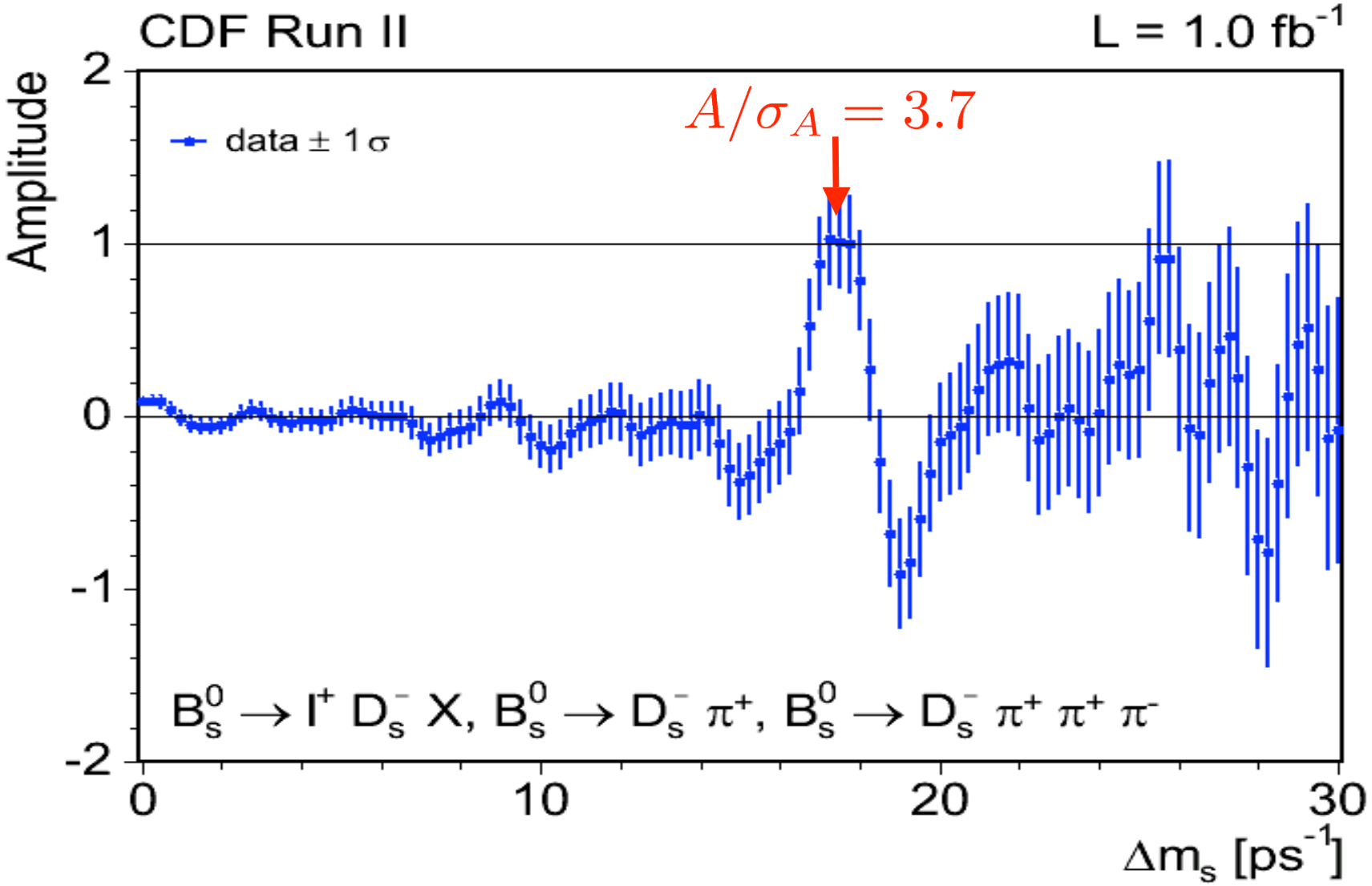
Amplitude Scan: B_s Mixing, 2006 World Average



Amplitude Scan: D0 B_s Mixing Search, March 2006



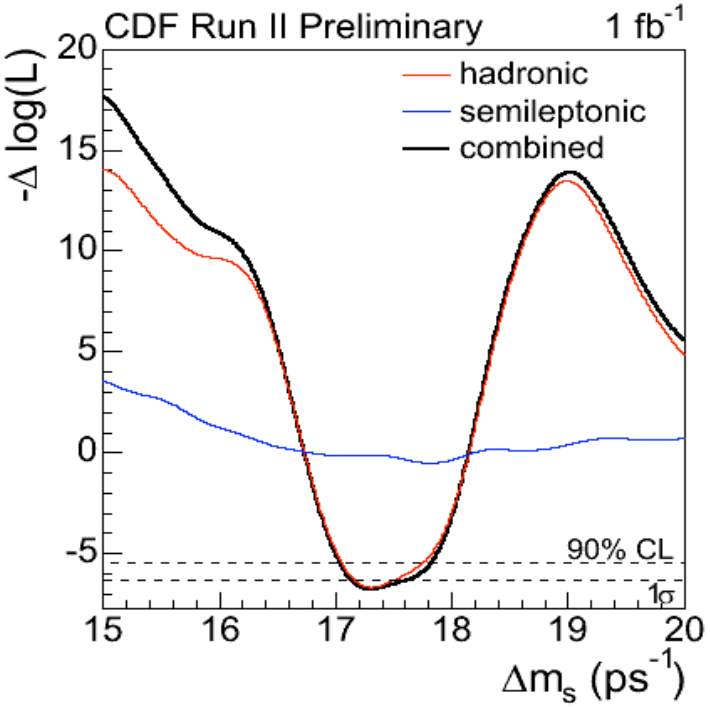
Amplitude Scan: CDF B_s Mixing Search, April 2006



Systematic Uncertainties & Result

- fit finds the oscillation frequency (Δm_s) most probable to match our data signature

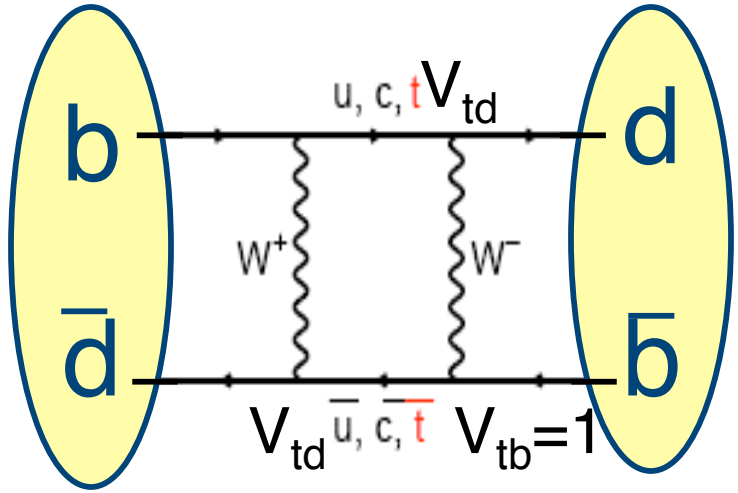
- systematic uncertainties
  - due to uncertainties of tracker geometry, alignm
  - roughly § 0.5%



$$\Delta m_s = 17.31^{+0.33}_{-0.18}(\text{stat}) \pm 0.07(\text{syst})\text{ps}^{-1}$$

Standard Model Prediction

- analogous diagram for B^0 mixing



$$\frac{\Delta m_s}{\Delta m_d} = \frac{m(B_s)}{m(B^0)} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

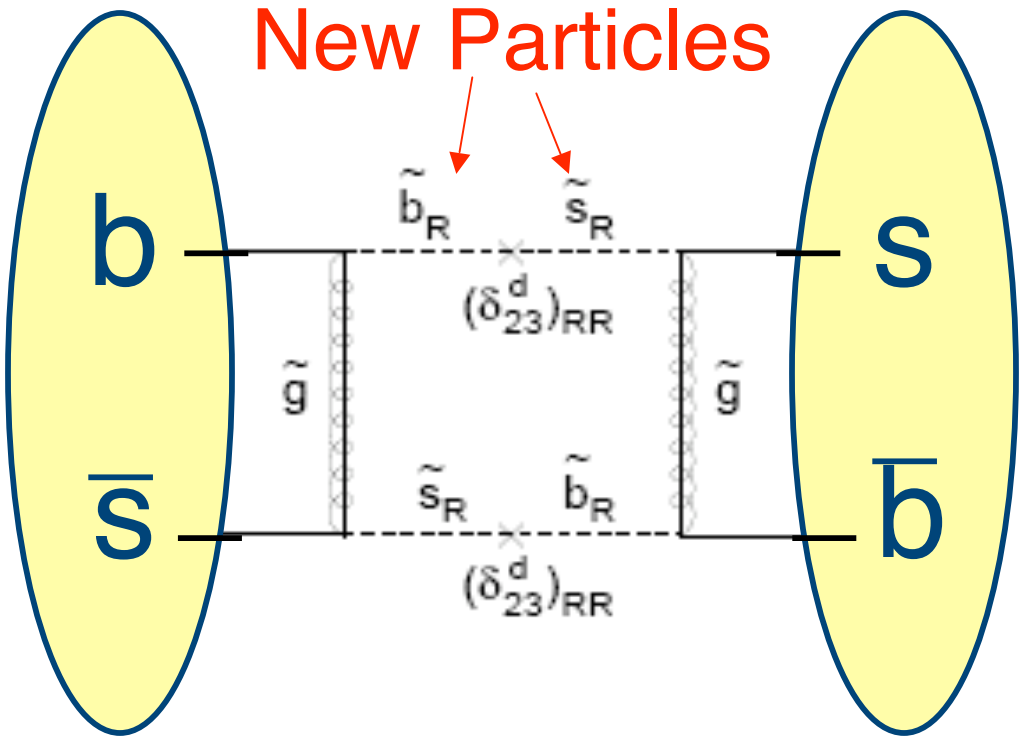
- global fit for W-quark coupling constants:

$$\Delta ms: 18.3\ ^{+6.5}_{-1.6}\ ps^{-1}$$

- our measurement agrees:

$$\Delta m_s = 17.31^{+0.33}_{-0.18}(\text{stat}) \pm 0.07(\text{syst})\text{ps}^{-1}$$

How would New Physics influence the B_s oscillation frequency?



- new particles in the loop change frequency
- new physics has evaded detection yet again!

A History of B Meson Oscillations (so far)

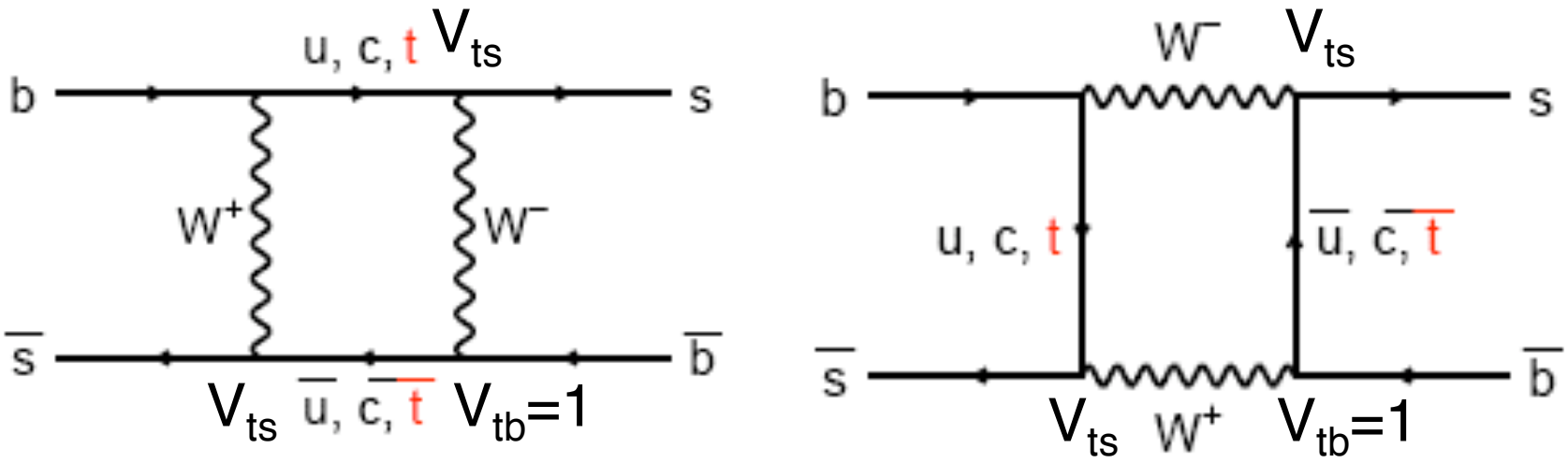
- 1987 UA1 evidence for B^0 and B_s mixing
- 1987 ARGUS observation of B^0 mixing
- (various detectors) improved measurements of B^0 mixing frequency (Δm_d)
- 2002: BaBar and Belle measure Δm_d at ~1%
- Tevatron "one-two punch" at B_s mixing:
  - March 2006: D0 sees hints of B_s oscillation
  - April 2006: CDF measures B_s oscillation frequency

The Future of B_s Oscillations

- the probability of a "fake" signal from the Tevatron experiments is still $p \sim 10^{-3}$
- the book is not closed until $p < 10^{-7}$ ("5σ")
- both detectors are taking more data
- also working on analysis improvements
- stay tuned for the exciting developments!
- CP violation is next:
  - is matter preferred over antimatter in B_s?

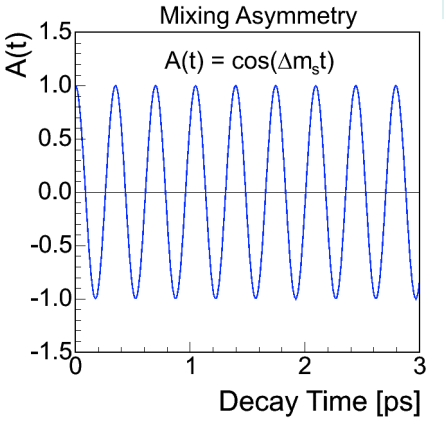
Supporting Slides

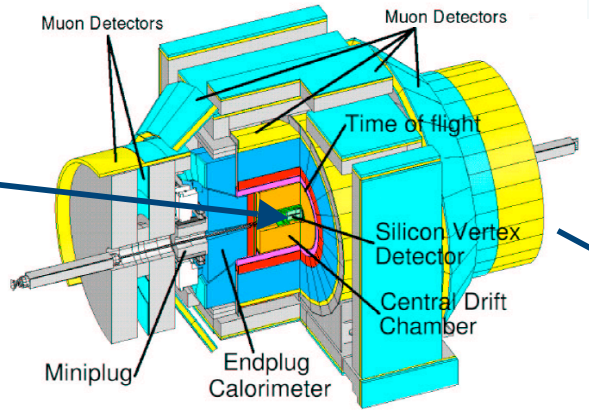
Why can the B_s meson mix?



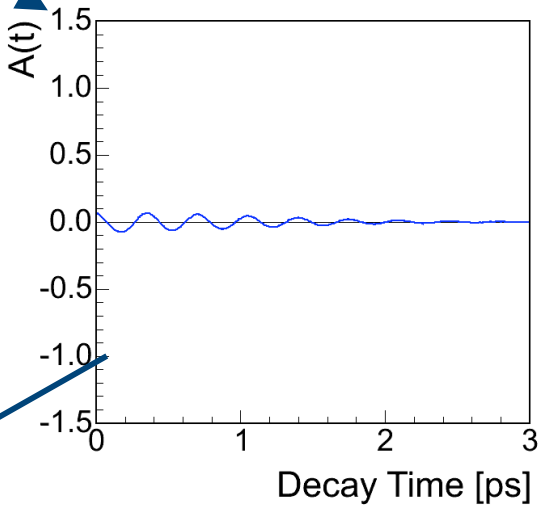
- simultaneous flavor change b! s, s! b
- mediated by W bosons

Real Measurement Layout





Data



momentum resolution
displacement resolution
flavor tagging power

scan for signal:

$A(\Delta m_s = 15\ ps^{-1}) = ?$

measure frequency:

$\Delta m_s = ?$

Unbinned Likelihood Fitter

$p \sim e^{-t/\tau}[1 \S AD \cos\Delta mt] - R(t)$

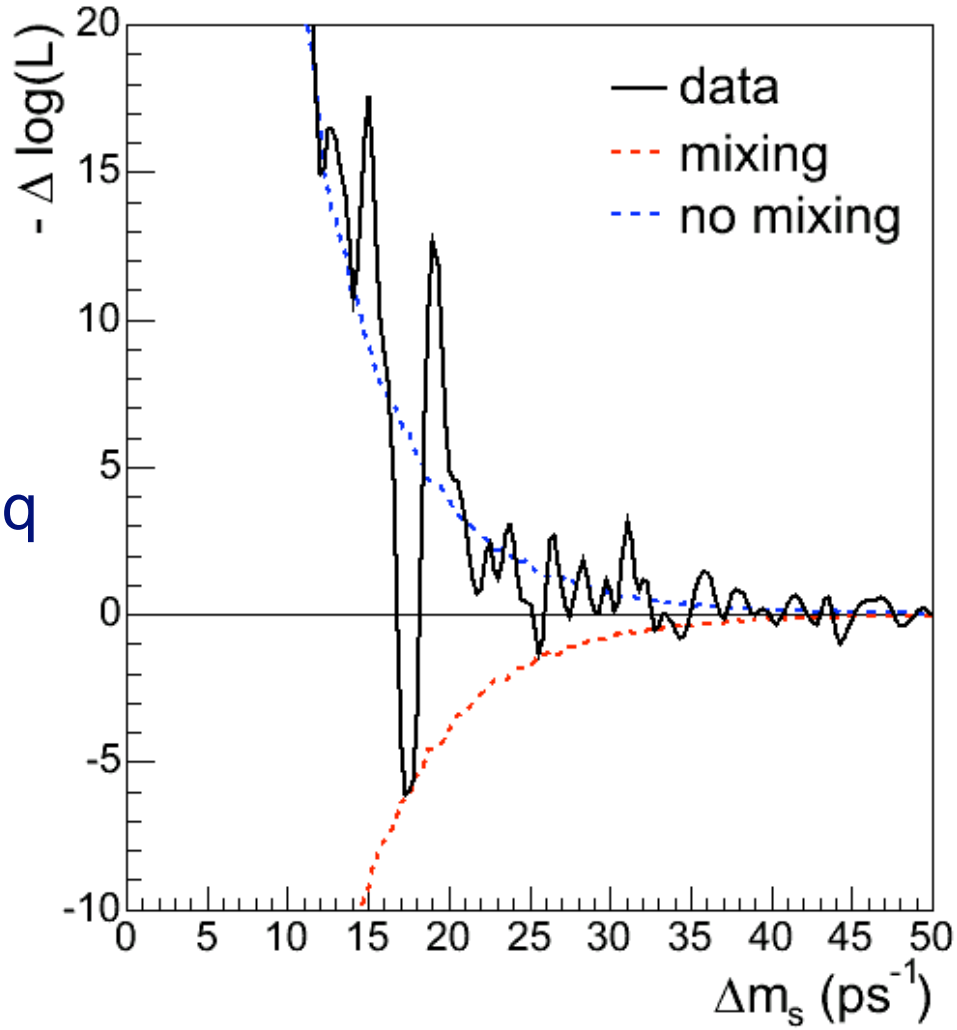
Likelihood Profile

mixing signal

$$\Delta \log(\mathcal{L}) = \log\left(\frac{\mathcal{L}(A=1)}{\mathcal{L}(A=0)}\right)$$

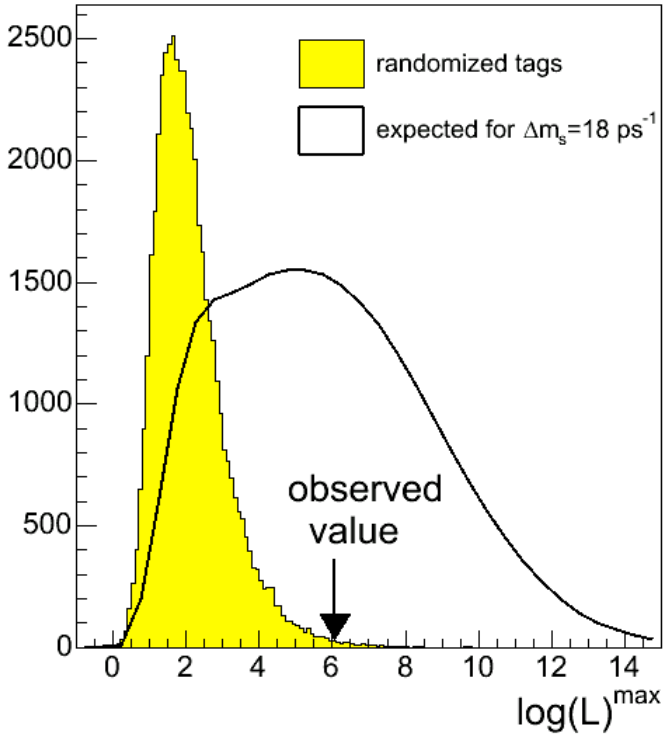
no mixing at given freq

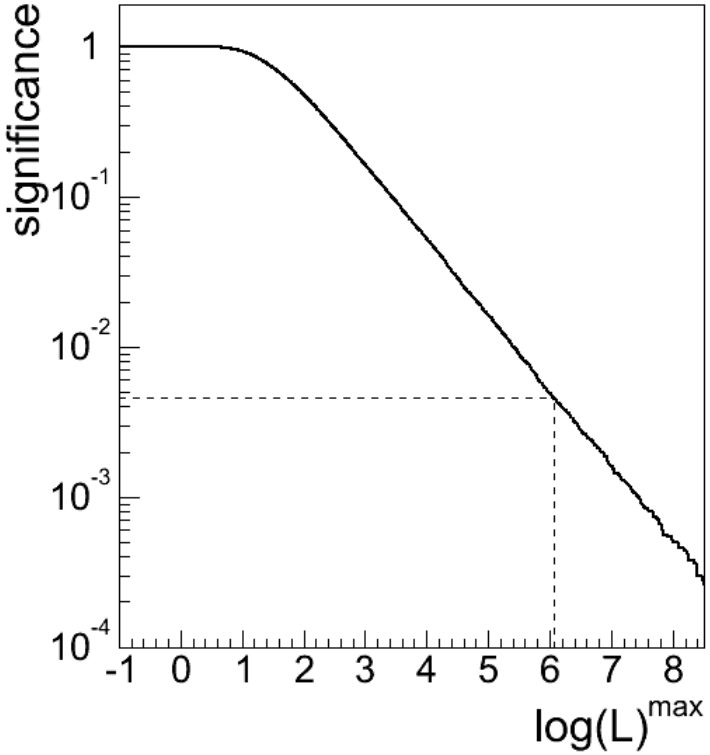
- probability “bump” at signal frequency



Probability of a “fake” signal

- compare to distribution of Δlog(L) for sample with randomized matter/antimatter tags





- probability of “random tag” conspiracy: 0.5%